The interaction of visual, vestibular, proprioceptive and auditory stimuli in the maintenance and control of postural sway behaviour

Vimonwan Hiengkaew

Submitted in accordance with the requirements for the degree of
Doctor of Philosophy

The University of Leeds
School of Biomedical Sciences

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The candidate confirms that the work submitted is her own and that appropriate credit has been given where reference has been made to the work of others.

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Special thanks are also expressed to the Royal Thai Government for financial support throughout this study.

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Finally, all the work contained in this thesis could not have been completed without the direction of God. Thank you Lord for all things you have done in my life, particularly for looking after me during my stay in the United Kingdom.

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Abstract

The individual and interactive effects of visual, vestibular, neck proprioceptive and auditory input on postural sway behaviour were examined in 80 healthy subjects (35 females, 45 males) aged 18 and 43 years old. The effects of static visual, vestibular and neck proprioceptor stimulation, both without and with auditory stimulation, as well as the effects of dynamic vestibular and neck proprioceptor stimulation, again without and with auditory stimulation, were examined. Comparisons were also made between static and dynamic vestibular and neck proprioceptor stimulation. In addition, the effect of gender on postural behaviour was also investigated.

The results show that visual feedback acts as a stabilising influence, whereas vestibular and neck proprioceptor stimulation, either static or dynamic, as well as auditory feedback have both a stabilising and a destabilising effect. Static vestibular stimulation improves postural stability more than dynamic stimulation. Static neck proprioceptive input and static vestibular-neck proprioceptor interaction leads to an increase in mediolateral and anteroposterior sway magnitudes, while dynamic input for both leads to anteroposterior stability. The visual-vestibular interaction influence on posture depends on the extent of the visual and vestibular agreement. The visual-neck proprioceptor interaction destabilises posture, as does the visual-auditory interaction. Static vestibular-auditory interaction improves anteroposterior stability, whereas the dynamic interaction leads to mediolateral and anteroposterior destabilisation. The neck proprioceptor-auditory interaction improves anteroposterior stability, but increases mediolateral instability. The visual-vestibular-neck proprioceptor, as well as visual-neck proprioceptor-auditory, interaction stabilises anteroposterior posture, whereas the visual-vestibular-auditory interaction destabilises mediolateral control. The vestibular-neck proprioceptor-auditory interaction with static vestibular and neck proprioceptive input causes postural stability, whereas dynamic stimulation leads to either postural stabilisation or destabilisation. Finally, the visual-vestibular-neck proprioceptor-auditory interaction appears to control the direction of movement. There appears to be a sex difference in postural maintenance due to the dominant role of the different sensory inputs in each gender.

It is concluded that the individual and interactive effects of visual, vestibular, neck proprioceptive and auditory inputs all influence postural maintenance. Pathways in the central nervous system for postural control are proposed, some of which are already known, while others are proposed on the basis of the findings presented in this study. The proposed pathways require further elucidation and investigation.

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List of abbreviations and symbol

Abbreviations

A	=	looking directly ahead
Ay	=	angle of sway measured from the sagittal plane
cm	=	centimetre(s)
CNS	=	central nervous system
COG	=	centre of gravity projection
COP	=	centre of pressure
E	=	neck extension
F	=	neck flexion
Hz	=	hertz(s)
L	=	neck rotation to the left
LE	=	neck rotation to the left and extended to rotation to the right and flexed
mm	=	millimetre(s)
mm/s	=	millimetre(s)/second(s)
ms	=	millisecond(s)
N	=	neck in neutral
R	=	neck rotation to the right
RE	=	neck rotation to the right and extended to rotation to the left and flexed
s	=	second(s)
Sa	=	magnitude of anterior sway
SD	=	standard deviation
Sl	=	magnitude of sway to the left direction
Sp	=	magnitude of posterior sway
Sr	=	magnitude of sway to the right direction
Sx	=	magnitude of mediolateral sway
Sy	=	magnitude of anteroposterior sway
TL	=	total path length
TLx	=	mediolateral path length

TLy	=	anteroposterior path length
Vm	=	mean sway velocity
Vxm	=	mean mediolateral velocity of sway
Vym	=	mean anteroposterior velocity of sway
X	=	mediolateral centre of gravity projection
Y	=	anteroposterior centre of gravity projection

Symbol

^{0}	=	degree(s)

Chapter 1

Introduction

The successful maintenance of the upright posture is dependent on the need to control the centre of gravity over the support surface (Gollhofer et al. 1989) and requires an intact sensory system, an integrating central nervous system (CNS) and an effective motor system. It is well documented that sensory inputs from the visual, vestibular and proprioceptor system, particularly from the neck and lower limbs, are all important in regulating balance. Moreover, the auditory system also appears to be influence postural control (Juntunen et al. 1987; Raper and Soames 1991; Kilburn et al. 1992; Soames and Raper 1992; Sakellari and Soames 1996).

The powerful effect of vision on postural control is well known to clinicians in the diagnosis of impairment of proprioceptive sensory input by eliminating the contribution of vision to postural stability (Romberg's test). Additionally, above knee amputees are reported to depend on visual input for their static balance maintenance (Dornan et al. 1978). Thus, the contribution of vision to postural control is important, especially when lower limb proprioceptive feedback is reduced. In normal healthy individuals standing with the eyes closed leads to greater postural sway than standing with the eyes open (Kollegger et al. 1989, 1992; Colledge et al. 1994): visual input is therefore crucially important to postural control. Nevertheless, visual input can lead to postural instability, for example, delaying or modifying visual feedback increases body oscillations and postural sway (Gantchev et al. 1981). Furthermore, increasing the eye-object distance causes an increase in both anteroposterior and mediolateral sway (Paulus et al. 1984). Furthermore, reversal of peripheral and central vision results in a marked deterioration of both anteroposterior and mediolateral sway (Yardley et al. 1992). Moving visual scenes also increases body sway in the direction of the stimulus (Dichgans et al. 1972; Bronstein 1986; Wolsley et al. 1996).

The important of the vestibular system on postural maintenance has been observed in vestibular deficient patients. Examination of patients with bilateral labyrinthine loss shows them to have increased body sway due to the loss of labyrinthine control of the antigravity muscles and head righting reflex (Tokita et al. 1981). Although the neck and ankle muscles of the patients respond to induced destabilistion, the ankle muscle's responses are significantly weaker and not effective in producing the required forward torque about the ankle joint (Keshner et al. 1987). In healthy individuals galvanic vestibular stimulation causes anterior or posterior sway (Magnusson et al. 1991; Fitzpatrick et al. 1994a; Inglis et al. 1995) depending on the polarity of the current (Magnusson et al. 1991; Inglis et al. 1995): the effect being due to changes in soleus and tibialis anterior muscle activity (Fitzpatrick et al. 1994a).

Both neck and lower limb propriception are reported to have an important role in postural control. Vibration of the paravertebral muscles in patients with neck tension shows a greater increase in anteroposterior and mediolateral sway than it does in healthy subjects, implying that the activation of afferent nerve endings may lead to insufficient postural responses (Koskimies et al. 1997). Vibration of splenius capitis on one side in normal adults induces a falling reaction and after the onset of vibration there is a subjective experience of forward tilt (Lund 1980). In addition, bilateral dorsal neck muscle stimulation while standing with eyes open and closed, as well as when sitting without support, produces a forward inclination of the whole body (Smetanin et al. 1993). However, the forward inclination observed when standing is replaced by backward head movement when the body is supported at the chest (Smetanin et al. 1993). Unilateral dorsal neck vibration is accompanied by the development of a lateral component in the postural response (Smetanin et al. 1993). Furthermore, right side neck stimulation evokes anterior body movement with some deviation to the left (Smetanin et al. 1993).

Lower limb proprioceptive input is clearly important in postural maintenance since patients with tabes dorsalis show an increased sway amplitude in the anteroposterior direction (Njiokiktjien and De Rijke 1972; Mauritz and Dietz 1980). Similar to the instability seen in tabes dorsalis patients, healthy individuals show a regular anteroposterior sway around 1Hz (Mauritz and Dietz 1980) after blocking group I afferents from the lower limbs by ischaemia. Additionally, hypothermia of the feet, both with and without calf muscle stimulation, increases sway velocity in the anteroposterior direction (Magnusson et al. 1990).

The auditory system has been reported to influence postural balance. With hearing loss at frequencies below 3000Hz subjects show faster sway velocities both with eyes open and closed (Kilburn et al. 1992). In addition, subjects exposed to high-energy noise also show increase body sway (Juntunen et al. 1987). In healthy individuals the influence of either stationary or moving auditory fields generally increases the magnitude of postural sway (Raper and Soames 1991; Soames and Raper 1992). Sakellari and Soames (1996) have demonstrated that some frequencies, as well as the loudness of sound, act as either stabilising or destabilising influences in both the mediolateral and anteroposterior directions.

The individual effect of the visual, vestibular, proprioceptive and auditory systems has been shown to be important for postural control. There is also evidence for the interaction of pairs of these systems for posture maintenance.

The interaction of vision and the vestibular system has been determined by asking subjects to adjust a laser pointer while sitting upright and looking ahead. Following vestibular stimulation, applied by cold water irrigation of the left external auditory canal, there is an illusion of motion and horizontal displacement of the body to the left (Karnath et al. 1994).

In addition to the visual and vestibular interaction, an interaction between vision and neck proprioception has also been reported. Dorsal neck vibration has shown target illusion and subjective horizontal body movement to the right with right-sided vibration and to the left with left side vibration (Karnath et al. 1994). Biguer et al. (1988) were able to show that when vibration of the left dorsal neck muscles began the visual target appeared to move to the right. When the vibration stopped the target moved rapidly to the left to its original position in the subjective midline. These results show that neck proprioceptive signals are involved in the determination and elaboration of the coordinates of visual space.

The interaction between vision and lower limb proprioceptive inputs show that during calf muscle stimulation with the eyes open there is an increase in anteroposterior, but not mediolateral, sway (Nakagawa et al. 1993). Moreover, vision reduces sway magnitude (Kollegger et al. 1989) and velocity (Day et al. 1993) more effectively when standing with the feet together than when the feet are apart. However, when full lower limb proprioceptive information is available the visual control of upright stance becomes less important (Bronstein 1986).

The interaction between vision and auditory stimulation has not been clearly established. Takeya et al. (1976) suggested that there is a possibility that postural sway could be controlled by a combination of visual and auditory feedback. The interaction between sound and vision leads to an increase in sway magnitude (Sakellari and Soames 1996). Furthermore, the work of Sakellari and Soames (1996) suggests that the auditory system is more dominant than the visual in maintaining balance in the mediolateral direction. However, no interaction between visual and auditory input in postural control has been reported (Raper and Soames 1991; Soames and Raper 1992).

The combination of vestibular and neck proprioceptive input has been observed by simultaneously applying left vestibular stimulation and left neck vibration, the result being a leftward displacement of subjective body orientation. The opposite is observed with left-sided vestibular stimulation and right-sided neck muscle vibration (Karnath et al. 1994).

Although the vestibular system influences the lower limb muscles, the potency of the vestibular influence depends on whether the vestibular information is required for postural stability (Fitzpatrick et al. 1994a). In situations where lower limb proprioceptive input is sufficient to control a stable upright posture the vestibular inputs do not appear to modulate leg muscle activity (Fitzpatrick et al. 1994b). However, vestibular and lower limb proprioceptive input appears to be able to substitute for each other when either is disrupted or absent (Horak et al. 1992) when elicited in the selection of the postural strategy to be used (Horak et al. 1990). Subjects with somatosensory loss, due to hypoxic anaesthesia of the feet and ankle, show an increase in hip strategy while bilateral vestibular loss patients lack a hip strategy (Horak et al. 1990).

Changes in postural maintenance in hearing loss individuals have been suggested as a result of vestibular damage (Juntunen et al. 1987). Although an interaction between the vestibular and auditory system has been suggested, Soames and Raper (1992) report that there is no such interaction in man. However, Soames and Raper (1992) reasoned that the intensity (65dB) used in their study was too low and that the frequency of the pure tone (250Hz) was not appropriate to reveal such an interaction.

From previous studies it is clear that combinations of visual, vestibular, proprioception and auditory stimuli influence postural balance. However, stimulation of the vestibular and proprioceptive systems has been via external sources such as electrical stimulation. In humans the head and neck contains the receptors for the visual, vestibular, neck proprioceptors and auditory system and moves during everyday activities. Thus, changes in head position, either static or dynamic, stimulate these receptors and may disturb the upright position and thus influence postural control and postural sway behaviour. Impairment or disturbance of either the visual, vestibular or lower limb proprioceptive input is counteracted by developing the contribution from the remaining two systems if normal static posture is to be maintained (Dornan et al. 1978; Okubo et al. 1980; Horak et al. 1990, 1992). This study hypothesises that in addition to visual, vestibular and proprioceptive input, auditory stimulation also influences postural control and thus also contributes to the maintenance of normal posture. This can be expressed as a simple equation:

Visual + Vestibular + Proprioceptive (mainly neck proprioceptive) + Sound	=	normal static equilibrium

Thus, the aims of this study are to determine the individual and interactive effects of visual, vestibular, neck proprioceptive and auditory input on postural sway behaviour under conditions of static and dynamic head movement.

Since there is some debate as to the effect of gender on postural control; males exhibiting greater (Soames and Atha. 1978; Juntunen et al. 1987; Kollegger et al. 1992) or lesser (Raper and Soames. 1991; Soames and Raper. 1992) sway than females, or no difference (Kollegger et al. 1989; Colledge et al. 1994; Wolfson et al. 1994; Hageman et al. 1995), plus the finding that vision has been reported to be more important in males than in females at all age group (Kollegger et al. 1992), the influence of gender on postural sway behaviour and its relationship to visual, vestibular, neck proprioception and auditory is also investigated.

The following hypotheses are therefore being tested:

H1. There is no difference in postural sway behaviour between males and females.

H2. There is no difference in postural sway behaviour

(a) with and without visual feedback

(b) with and without vestibular stimulation

(c) with and without neck proprioceptor feedback

(d) with and without auditory stimulation

H3. Interactions between visual, vestibular, proprioceptor and auditory stimulation have no influence on postural sway behaviour.

H4. There is no difference in postural sway behaviour under conditions of static and dynamic stimulation for

(a) vestibular stimulation

(b) neck proprioceptor stimulation

Chapter 2
Literature review

2.1 Postural maintenance

2.1.1 The centre of gravity (COG) and centre of pressure (COP) of the body

The human body is a non-rigid system composed of many segments, for example the head and the trunk, whose mass is derived from the summation of the individual segment masses. According to Newton's laws and D' Alembert's principles, under the influence of a gravitational field, the intersection of the forces on each of the body segment masses reaches a new position for the force line known as the COG of the body (Roberts 1995). In erect standing the COG of the body lies about 57% of the full height from the ground for adults males. For adult females it lies about 55% of the full height from the ground due to their heavier pelvis and lighter thorax, arms and shoulders (Page 1978). However, the body's COG is located at approximately the level of the second sacral vertebra, the bony prominence at the top of the natal cleft (Hollis 1985).

The COG of the body relative to the support surface plays a major role in the stabilisation of human posture (Gollhofer et al. 1989). Figure 2.1 shows that the COG of the body changes as posture changes. The change of the body's COG location is related to the change in position and movement of body segments (Murray et al. 1975) as a result of torques generated by the moving segment(s) (Kreighbaum and Barthels 1996): the COG of the body may lie inside or outside the body (Adrian and Cooper 1995). To maintain balance, the COG of the body is adjusted in relation to the line of gravity and the supporting surfaces (Roberts 1995). As shown in Figure 2.2 the COG of the body finds a new equilibrium position when the dimensions of the support base change. If the line of gravity is close to the edge of the support base or falls outside it, the body become unstable and balance may be lost (Hollis 1985; Kreighbaum and Barthels 1996).

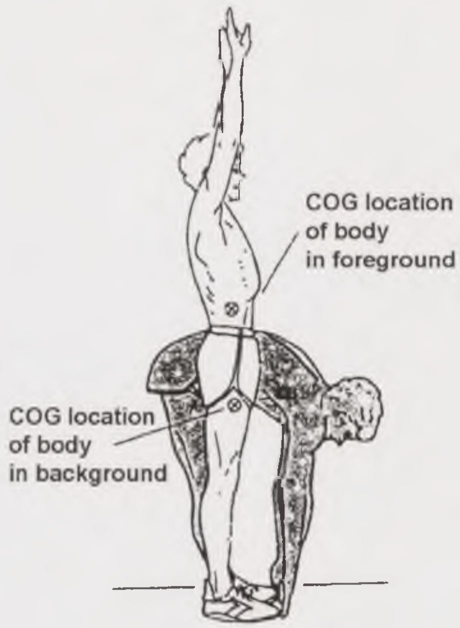


Figure 2.1 **The change in position of the centre of gravity (COG) of the body as the body changes shape. In the forward bending posture the COG of the body lies outside the body (taken from Kreighbaum and Barthels, 1996).**

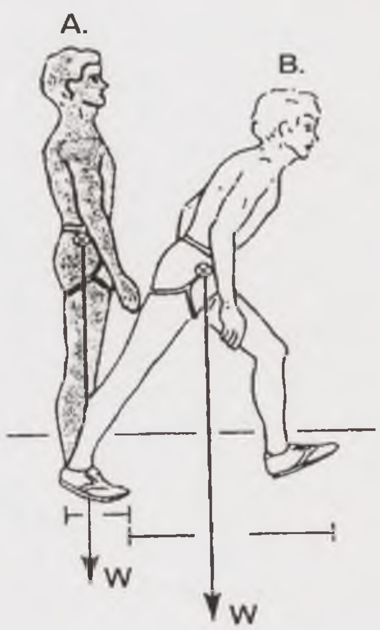


Figure 2.2 **Alignment of the centre of gravity of the body relative to the gravity line and the base of support; A. narrow base of support and B. wide base of support (taken from Kreighbaum and Barthels, 1996).**

The centre of pressure (COP) of the body is the centre of total force distribution applied to the support surface (Murray et al. 1975). The magnitude and location of the forces are under the control of all muscles associated with posture and balance. Hence, the COP of the body is the net neuromuscular response to control of the passive body COG (Winter et al. 1996).

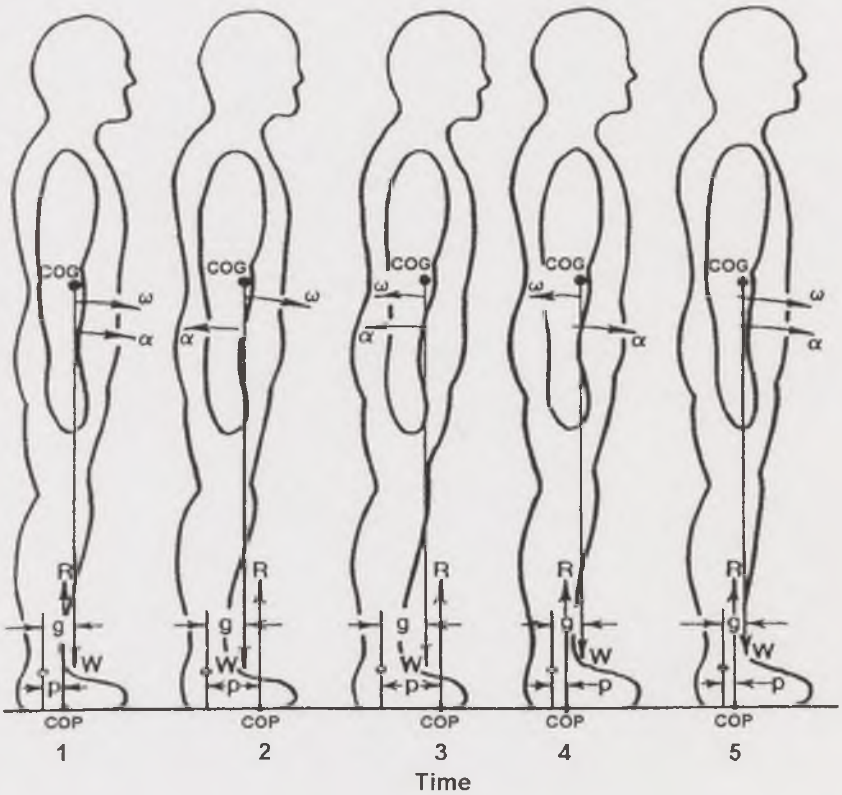


Figure 2.3. The balance of the body centre of gravity (COG) is under control of the body centre of pressure (COP) during quiet stance (taken from Winter et al. 1996).

The distinction and relationship between the body COG and COP are shown in Figure 2.3. During erect standing with feet together back and forth movement occurs in the sagittal plane. At time 1 the COG is in front of the COP and is moving forward with an angular velocity ω. Body weight W is equal and opposite to the vertical reaction force R, with W and R working at distances g and p respectively, from the ankle joint. If the body is behaving like an inverted pendulum about the ankle, a counter-clockwise moment equal to Rp and a clockwise moment equal to Wg will be acting. Since g is greater than p, Wg will be greater than Rp and the body will experience a clockwise angular acceleration α.

To control the forward angular velocity the COP will be increased due to activation of the plantarflexors so that at time 2 the COP is forward of the COG. Rp is now greater than Wg. Therefore, the angular acceleration is now backward to reduce the forward angular velocity. At time 3 the backward angular acceleration has reversed the angular velocity so that both are now counter-clockwise and the body is undergoing backward movement. When the central nervous system (CNS) perceives that the backward movement of the COG requires to be adjusted, the motor control system decreases plantarflexor activation. As a result the COP shifts toward the COG. Thus, at time 4 angular acceleration has again become clockwise and after a period of time the angular velocity decreases and reverses. The body will return to its original conditions as can be seen at time 5. From these sequences it can be seen that the COP continues to move backward and forward so as to control the COG of the body. The COP is the neural control variable whereas the COG is the controlled variable (Winter et al. 1996).

2.1.2 Postural sway

Postural sway is the continuous active movement of the COG of the body around the equilibrium point, restoring the disequilibrium produced by body oscillation and, eventually, causing a small displacement of the COG of the body (Norré 1990). The oscillation is the result of a physiological delay in the motor feedback circuit (Pal'tsev and Aggashyan 1974). Postural sway is produced by spinal, trunk and limb muscular activity working reflexly and the fine control of the CNS (Norré 1990; Roberts 1995; Kreighbaum and Barthels 1996).

From a study of postural responses in relation to the support surface in standing humans two basic postural sway strategies have been formulated. The ankle strategy is the activation pattern that the primary forces use to move the COG of the body at the ankles. It is elicited by activity primarily in muscles crossing the ankle joint and then sequentially spreading to the thigh and then the trunk muscles. The hip strategy is the primary action to move the COG of the body about the hip and is elicited by trunk rotation through active hip motions (Horak and Nashner 1986). The ankle strategy is, therefore associated with a distal to proximal pattern of ankle-knee-hip muscular activation, whereas the hip strategy is associated with a proximal to distal sequence. However, combinations of ankle and hip strategies can be observed (Horak and Nashner 1986; Winter et al. 1996). In conditions in which both the ankle and hip strategy are insufficient a distinctive postural strategy, the stepping or stumbling strategy, comes into effect (Nashner and Forssberg 1986). The ankle and hip strategy adjust balance by restoring the COG of the body over a fixed support surface, whereas the stepping or stumbling strategy restores equilibrium by moving the base of support under a falling COG (Horak and Nashner 1986). The strategies for postural movements depend not only on the support surfaces (Horak and Nashner 1986), but also stance positions (Winter et al. 1996).

Postural sway can be observed in the frontal plane (mediolateral sway) and sagittal plane (anteroposterior sway). In normal quiet stance mediolateral sway is under the control of the hip strategy, whereas anteroposterior sway is under the control of the ankle strategy (Day et al. 1993; Winter et al. 1996; Gatev et al. 1999). When standing with the feet together the role of the ankle and hip strategies are enhanced in mediolateral sway, while in anteroposterior sway the role of the ankle strategy is reduced but that of hip is increased (Gatev et al. 1999).

The frequency of postural sway observed using force platforms shows at least two clearly visible frequency spectra: a low and a high component. The low frequency body sway is at about 0.3 Hertz (Hz), whereas the high is at about 1-2Hz (Njiokiktjien and De Rijke 1972). The low component of postural sway frequency does not occur in all people and is sometimes hardly seen. This frequency is probably of a vestibular origin (Njiokiktjien and De Rijke 1972). Visual input controls postural sway frequency below 1Hz (Dichgans et al. 1976), whereas the frequency above 1Hz reflect balance movements controlled by proprioceptive mechanism (Dichgans et al. 1976; Nakagawa et al. 1993). The frequencies of body sway are observed in both the mediolateral and anteroposterior directions of which frequency component are spread between 0.30-1.05Hz for the mediolateral component and 0.15 and 1.30Hz for the anteroposterior component (Soames and Atha 1982).

2.1.3 Postural balance function

The role of postural balance is to provide a stable connection between the body and the environment. The two styles of reference; geometric, the position of body segments relative to the external world, and kinetic, the distribution of the body mass with respect to the support surface, are employed in the organisation of the interrelation between the body and the surroundings (Massion et al. 1998). Postural control can be considered to have two main strategies, stabilisation of head position and maintenance of the erect posture. The object of the first is to stabilise the visual field, while that of the latter is to maintain an upright position against disturbing influences (Norré 1990).

The head contains the two most important perceptual systems, the visual and vestibular system, for the detection of self-motion in space and head position in space (Carpenter 1990) using a simple frame of reference (Pozzo et al. 1990). Stabilisation of the head is the task of the neck muscles (Roberts 1995). The head can be stabilised on the trunk in one of two ways. Firstly, an articulated mode in which it moves freely, and secondly, an en bloc mode in which it moves with the trunk (Shumway-Cook and Woollacott 1995). During head movement the eyes move relative to the skull with the same velocity and in the same plane as the head movement to maintain a constant image projected onto the retina (Norré 1990). Ocular reflexes, consisting of the vestibulo-ocular, optokinetic and cervico-ocular reflexes accomplish eye movement (further details are given in part 2.2.2). During body movement the head is arranged in different positions in order to direct the gaze for maintaining perception of the surrounding image on the same place of the retina (Pozzo et al. 1990). The stabilisation of head position during body movement can be adjusted by spinal reflexes consisting of the vestibulospinal, vestibulocollic, cervicocollic and cervicospinal reflexes (further details are given in part 2.2.2). If there is retinal slip the surroundings are perceived as moving and will influence postural stability (Dichgans et al. 1972; White et al. 1980). Furthermore, the control of head position also depends on ankle somatosensory input (Di Fabio and Anderson 1993).

Maintenance of the upright posture comprises two parts: the first is head stabilisation and the second is constancy of the erect position. Both are dependent on spinal reflexes adapted and controlled from higher centres in the CNS in relation to the sensory information presented (Norré 1990). A number of antigravity muscles are required to maintain the stability and orientation of the head, trunk and limbs. The location of the head and/or trunk with respect to the sagittal plane serves as a reference frame both for body position and movement perception with respect to the environment, and to limb movement regulation in the surrounding space (Pozzo et al. 1990).

2.1.4 Various influences on postural maintenance

The maintenance of postural balance as a function of the CNS requires intact sensory inputs and effective motor outputs (further details are given in part 2.2). Degeneration of the CNS, as well as of the afferent and efferent organs, directly influences postural sway (Dichgans et al. 1976; Okubo et al. 1980; Tokita et al. 1981; Black 1982; Ishizaki et al. 1988; Tian et al. 1992). Furthermore, postural sway is influenced by various other secondary factors.

Age influences balance function in a negative way, seen as frequent falls in the elderly through either tripping or postural falls. Postural sway increases non-linearly with age in both males and females (Overstall et al. 1977; Kollegger et al. 1992; Whipple et al. 1993). The mean COG projection near to the centre of the support base is consistent at all ages, but the magnitude of sway about the base centre tends to be larger in the very young and the very old (Hasselkus and Shambes 1975; Norré 1990): anteroposterior sway is age-related in males but not in females, while mediolateral sway is lower between 36-50 years compared with ages 21-35 and 51-65 years in both males and females (Kollegger et al. 1992). The change in sway with age is due to peripheral proprioceptive cue reduction (Overstall et al. 1977), visual distortion (Whipple et al. 1993), long movement time and less accuracy (Hagemann et al. 1995), and changes in the central control of posture (Hasselkus and Shambes 1975).

The effect of gender on postural balance has not been resolved. Some investigators have reported that males show more (Soames and Atha 1978; Juntunen et al. 1987; Kollegger et al. 1992) or less (Raper and Soames 1991; Soames and Raper 1992) postural sway than females, while others have observed no difference (Kollegger et al. 1989; Colledge et al. 1994; Wolfson et al. 1994; Hageman et al. 1995). Among the postural sway differences between males and females the direction of sway has been reported to be important. Anteroposterior sway in the men appears to be less than in women in the young (Soames and Atha 1978), but more in the middle and older age groups (Kollegger et al. 1992). Mediolateral sway in males is greater than in females in both the young and older age groups (Soames and Atha 1978; Kollegger et al. 1992). The mechanisms underlying these gender differences in postural control have yet to be clearly identified. However, Kollegger et al. (1992) have reported that visual feedback in all age groups is more important in males than in females.

The effect of alcohol on postual control is well known. Alcohol-dependent patients shows postural control impairment caused by a dose-dependent toxic effect of alcohol (Wöber et al. 1999). Postural imbalance by alcohol increases anteroposterior body sway (Wöber et al. 1999). Alcohol decreases postural stability by reducing the function of the oculomotor system, the vestibulo-ocular reflex and the vestibular system (Tianwu et al. 1995).

An effect of cigarette smoking on anteroposterior sway has been recorded in habitual and occasional smokers. After the last inhalation of smoke body sway exhibits higher frequencies and shows greater amplitude than normal body sway. This finding suggests that nicotin absorbed into the blood during smoking affects the structures in the brainstem related to the regulation of standing posture (Uchida et al. 1980).

Occupation is also a secondary influence on postural control, with workers exposed to industrial solvents, lead and high-energy noise, having poorer postural stability than controls (Juntunen et al. 1987; Ledin et al. 1989; Kilburn et al. 1992; Chia et al. 1994). These toxic influences act to cause impairment of the postural afferent systems and the CNS (Ledin et al. 1989, Bhattacharya et al. 1990; Chia et al. 1994). High-energy noise is harmful to the vestibular system (Juntunen et al. 1987).

There is also a psychological component influencing postural control. Patients with psycho-organic syndromes due to industrial solvent exposure, exhibit greater sway than do controls (Ledin et al. 1989). Sleep deprivation also causes deficiency in attention and performance in a variety of cognitive tasks, consequently the ability to maintain standing and control balance appears to be diminished in sleep deprivation; this may be due to motor inhibition (Schlesinger et al. 1998).

2.2 The postural-regulating system

Postural control utilises sensory information from a variety of sources, which then interact centrally to produce the required adjustments to movements. Thus, successful postural maintenance needs an intact afferent input, an integrating CNS and an effective efferent output system.

2.2.1 Afferent input

The main sensory inputs for postural control are the visual, vestibular and proprioceptive systems. Additionally, the auditory system is reported to involve in postural maintenance (Juntunen et al. 1987; Raper and Soames 1991; Kilburn et al. 1992; Soames and Raper 1992; Sakellari and Soames 1996).

Visual input

Impulses from the retina project to and synapse in the lateral geniculate nucleus, and then to the primary visual cortex in the calcarine area of the occipital lobe via the optic radiations (Livingston 1990; Martin 1991; Pansky et al. 1992; Purves et al. 1997). In addition, visual information bypasses the lateral geniculate nucleus, projecting to the midbrain, the superior colliculus and the pretectal nuclei. The function of the superior colliculus in humans is not known, however it is probably involved in the regulation of eye and head movement in response to visual stimuli. The pretectal nuclei participate in pupillary as well as other visual reflexes (Martin, 1991; Pansky et al. 1992; Purves et al. 1997).

The visual system initially fixes the eyes on a stationary or moving object, secondly, it scans the visual field and, finally, stabilises the visual field during head or body-head combination movements (Fleming et al. 1969). Two visual input mechanisms related to postural balance are retinal slip and the visual proprioceptive system (Carpenter 1990; Norré 1990). The retinal slip generates input for adaptive eye movement consisting of a foveal part, stimulating the optokinetic and pursuit system, and a peripheral retinal part, stimulating the optokinetic system (Norré 1990). The ocular proprioceptive system is responsible for controlling gaze direction in visually-oriented activities to build up a directional frame of reference taking into account whole-body posture leading to the initiation of suitable eye movement reflexes and postural regulation (Roll et al. 1991).

Visual stimuli subserve the perceptual interpretation of the head in space (Guitton et al. 1986; Carpenter 1990; Pozzo et al. 1990; Kanaya et al. 1995), the eye in space (Carpenter, 1990), the eye relative to the head (Wolsley et al. 1996), self-motion and object-motion (Paulus et al. 1984; Clément et al. 1988).

Closing the eyes while standing with the feet together, the Romberg test, has long been used for testing patients who have proprioceptive sensory impairment, clearly showing the powerful influence of vision on postural stabilisation. Postural assessment with and without visual input has been established as a routine part of many experiments (Kollegger et al. 1989, 1992; Toupet et al. 1992; Colledge et al. 1994). The stabilisation effect of vision is mainly by the central visual field and exhibits a powerful contribution to the control of mediolateral sway (Paulus et al. 1984).

In normal stance with eyes open, although visual feedback usually improves body stabilisation, it appears to lead to postural destabilisation (Gantchev et al. 1981). An increase in eye-object distance causes an increase in postural sway in both the anteroposterior and mediolateral directions, due to a smaller angular displacement of the image on the retina leading to physiological imbalance known as height vertigo (Bles et al. 1980; Brandt et al. 1980; Paulus et al. 1984). Using a head-mounted mirror and prism results in a marked deterioration of sway similar to standing with the eyes closed and, moreover, causes a selective decrement in visuo-spatial memory task performance (Yardley et al. 1992). Moving visual scenes primarily cause the body to shift in the direction of the stimulus followed by an adjustment in the direction opposite to the moving stimulus (Dichgans et al. 1972; Bronstein 1986).

Visual input can compensate for other inadequate afferent inputs. The compensation of visual input is apparent in body sway correction in bilateral vestibular deficit patients (Allum and Pfaltz 1985; Keshner et al. 1987; Paulus et al. 1987), as well as in above-knee amputees (Dornan et al. 1978). Furthermore, vision partially compensates for head control in labyrinthine defective subjects (Kanaya et al. 1995). With a narrow stance width visual input helps to minimise anteroposterior sway (Day et al. 1993). When the soles are anaesthetised by hypothermia the increase in body sway is significantly less with the eyes open than with the eyes closed, elucidating the compensatory nature of visual input in maintaining postural control (Magnusson et al. 1990). The major function of the visual system is for adapting to various environmental conditions using feed-forward control (Nashner and Berthoz 1978).

Vestibular input

Vestibular input is detected by the three semicircular canals (anterior, posterior and horizontal) and the two otolith organs (saccule and utricle) on each side of the head. The semicircular canals respond to head rotation (Carpenter 1990; Purves et al. 1997; Sherwood 1997) and provide information about angular movement: they are sensitive to acceleration. The otolith organs detect static displacement, linear acceleration and the position of the head and body relative to gravity (Carpenter 1990; Mira 1995; Purves et al. 1997), with the utricle being influenced by lateral head tilt and the saccule by up and down head movements (Norré 1990; Pansky et al. 1992). The receptors of the anterior and horizontal semicircular canals and the utricle are innervated by the superior part of the vestibular division of the eighth cranial nerve, whereas those of the posterior semicircular canal and saccule are innervated by the inferior part. The vestibular nerve terminates in four nuclei (lateral, medial, superior and inferior) in the rostal medulla and caudal pons. The vestibular nuclei project to several parts of the brain. Firstly, to the upper brainstem via the medial longitudinal fasciculus for controlling eye, head and neck movement. Secondly, to cervical and upper thoracic segments via the medial vestibulospinal tract for the control of head position, as well as to the full length of spinal cord via the lateral vestibulospinal tract for controlling limb muscles. Thirdly, to the cerebellum via the juxtarestiform body influencing co-ordination of the axial muscles of the neck and vertebral column. Finally, to the brainstem reticular formation which results in nausea, vomiting and sweating in relation to vestibular stimulation (Martin 1991; Pansky et al. 1992). Furthermore, the vestibular nuclei transmit information to the parietal lobe, Brodmann's area 5 of the cerebral cortex via the ventral posterior thalamic nucleus, which is thus involved in the perception of the position of the body in space and body acceleration, thereby controlling body movement and perceiving vertigo (Martin 1991; Purves et al. 1997).

The vestibular system provides control mainly in the low frequency range of body sway (Njiokiktjien and De Rijke 1972; Dietz et al. 1988; Nakagawa et al. 1993) and perceives movement of the head (Carpenter 1990; Norré 1990), trunk and limbs (Bussel et al. 1980; Mergner et al. 1991). It contributes to any of several functions in postural control. Firstly, the vestibular system acts to stabilise the visual field (Norré 1990) and head (Guitton et al. 1986; Pozzo et al. 1990) for completing the first goal of postural balance. Secondly, it serves to determine head motion and head position in space (Mergner et al. 1991, 1992), as well as organising object-motion and self-motion (Mergner et al. 1992; Kolev et al. 1996). Thirdly, since the vestibular signals are important for head motion velocity they could also be important for modulating the amplitude of postural responses (Keshner et al. 1987) and selecting the appropriate postural sway strategies (Horak et al. 1990). Fourthly, the vestibular system could provide information to promote the CNS internal representation of the direction of gravity and then direct body muscle activity (Black 1982; Fitzpatrick et al. 1994a), thus acting as an internal reference system to control the erect position (Nashner et al. 1982; Inglis et al. 1995). To maintain vertical equilibrium the vestibular system performs two significant functions within a hierarchically organised system. At a low level it weighs the sum of the orientation inputs derived from the vestibular apparatus, as well as the proprioception and visual systems, to directly mediate postural muscle activity. At a higher level it provides an orientation reference for the rapidly reacting proprioception and visual input (Nashner et al. 1982). Finally, particularly during fast postural movements, the vestibular system may play an extensive role in determining the final equilibrium position of the postural response (Inglis et al. 1995).

The vestibular system is judged to be most important for postural balance when other sensory input information is reduced, principally when sway is around 1Hz (Mauritz and Dietz 1980) or during motion (Martin 1965). However, the compensatory contribution of the vestibular system is of minor importance, being generally limited to the compensation of body sway in the low-frequency range (Dichgans and Diener 1989): it plays no role in activating the initial postural responses (Inglis et al. 1995). In body sway adjustment the mechanism of the vestibular system does not provide sufficient compensatory electromyographic responses during rapid horizontal foot movement (Dietz et al. 1988). Moreover, with the eyes closed, an intact peripheral vestibular system is not essential to the adjustment of sway stabilising reactions (Keshner et al. 1987). However, in the dark the semicircular canals provide head stability (Guitton et al. 1986).

Proprioceptive input

The sensory receptors of the proprioceptive system, the joint and muscle receptors, are known to provide information about the position and movement of the body during postural control (Njiokiktjien and De Rijke 1972; Mauritz and Dietz 1980). Additionally, cutaneous receptors also contribute to balance maintenance (Magnusson et al. 1990; Kavounoudias et al. 1998). The receptors of the proprioception system transmit information which terminates in the ventral posterolateral nucleus of the thalamus. The neurones then project to the parietal lobe of the cerebral cortex and the primary somatosensory cortex. In addition, information is sent via the medulla to the cerebellum (Martin 1991; Pansky et al. 1992).

• Neck proprioceptive input

The receptors in the cervical region play an important a role in postural control and can be considered as a secondary labyrinth (Manzoni et al. 1979). Neck proprioception provides information about movement or change of head position (Abrahams 1977) and head and body position in space (Mergner et al. 1991, 1992; Smetanin et al. 1993; Karnath et al. 1994). Moreover, it signals the position of the head relative to the trunk, head velocity relative to the trunk and head-eye co-ordination (Lund 1980; Biguer et al. 1988). These assist visual field stabilisation and maintenance of the upright position.

In patients with total loss of vestibular function neck input aids gaze stabilisation, a strategy which may rely on the latency of the cervico-ocular reflex during active head movements (Kasai and Zee 1978). In addition, neck and/or upper somatosensory input can substitute for the missing vestibular trigger by increasing the somatosensory loop gain (Horak et al. 1992). In the dark, neck inputs combining with the vestibular system provide self-motion perception (Mergner et al. 1991). Thus, neck inputs appear to combine with other afferent inputs to control posture when there is a deficiency in other systems.

• Lower limbs proprioceptive input

During standing the proprioceptors of the soles of the feet, as well as those of the ankle joint and muscles, contribute to postural control (Mauritz et al. 1980;

Horak and Nashner 1986; Nakagawa et al. 1993; Kavounoudias et al. 1998). Lower limb proprioception is reported to predominate in the control of high frequency body movement (Dichgans et al. 1976; Nakagawa et al. 1993). The performance of the ankle-foot proprioception input relies on the nature of the support surface as illustrated by a change in postural control strategy (Horak and Nashner 1986; Horak et al. 1990). Cutaneous afferent input from the sole of the feet is important for postural control (Magnusson et al. 1990) as it informs about the body position with respect to the vertical reference and triggers appropriate postural responses (Kavounoudias et al. 1998). Furthermore, the somatosensory inputs from the feet and ankle have been suggested to help control head position (Di Fabio and Anderson 1993). Lower limb proprioception, mainly from the ankle joint, is used to trigger and modulate ankle muscle responses and help to form other postural reactions (Bloem et al. 1998). Movement about the ankle joint is dominant only for the mediolateral frontal plane with a stance width less than eight centimetres, whereas motion of the trunk and legs occurs with increasing stance width conditions (Day et al. 1993). In stable upright standing the signals from the leg muscles are reported to be sufficient for postural maintenance (Fitzpatrick et al. 1994b).

Although lower limb proprioception input plays a smaller, but nevertheless important, role in maintaining posture than does visual information (Kollegger et al. 1989; Nakagawa et al. 1993), without vision the proprioceptive cue contributes to the control of high-frequency body sway (Nakagawa et al. 1993). Displacement of the support surface during stance induces early functionally directed responses in the lower and upper leg muscles (Dietz et al. 1988). Lower limb proprioception probably compensates during active maintenance of the standing posture in cases of labyrinthine loss (Bussel et al. 1980). Bilateral vestibular loss patients use the ankle strategy and not the hip strategy to maintain the erect posture (Horak et al. 1990).

Auditory input

Humans can detect sounds in the frequency range 20Hz to 20,000Hz. Auditory sensory hair cells transform vibrational energy into electrical signals. The information pass along the auditory nerve and terminates in the dorsal and ventral cochlear nuclei. Ascending to the auditory cortex, the information is transmitted via the lateral lemniscus to the inferior colliculus then to the medial geniculate nucleus, and finally to the primary auditory cortex via the auditory radiation (Martin 1991; Pansky et al. 1992; Purves et al. 1997).

The influence of the auditory system on postural control has been observed in hearing loss subjects, who show postural instability, implying involvement of the auditory system in postural control (Juntunen et al. 1987; Kilburn et al. 1992). The frequency of sound appears to affect anteroposterior sway regulation, whereas loudness has a tendency to influence mediolateral sway control (Sakellaki and Soames 1996). In addition, Schaefer et al. (1981) demonstrated that moving acoustic signals influence eye movements. The saccadic response to auditory stimulation has a longer latency and slower peak velocity than the response to visual stimuli (Lueck et al. 1990). Moreover, an appropriate auditory stimulation influences circularvection (Marme-Karselse and Bles 1977).

The presence of an auditory field, both stationary and moving, has been shown to have a destabilising effect on postural sway behaviour (Raper and Soames 1991; Soames and Raper 1992). The direction of the sound source and the type of auditory input are, however also important. When the sound source is a pure tone moving from side to side it causes greater mediolateral sway than does a sound moving anteroposteriorly. Similarly, an anteroposterior moving sound produces greater anteroposterior sway than side to side movement (Soames and Raper 1992). Pure tone increases mediolateral sway more than does conversation (Raper and Soames 1991). Some sound frequencies, for instance 346Hz and 842Hz, have a stabilising effect on anteroposterior sway, whereas others, for example 45Hz and 997Hz, have a destabilising effect (Sakellari and Soames 1996).

2.2.2 Integrating central nervous system

CNS organisation of sensory input

The selection of postural movement strategies by the CNS is influenced by former experiences (Horak and Nashner 1986; Horak et al. 1989), as well as by current sensory input information (Horak and Nashner 1986; Diener et al. 1988; Horak et al. 1989). As shown in Figure 2.4 incoming sensory information is compared with the stored reference patterns, provided by prior experiences, and is processed subconsciously. If the harmonious incoming sensory information is a known pattern, further processing (reflexes and voluntary control) produces the appropriate reflexive compensatory movements of the eye and spinal muscles (Norré 1990). If there is a sensory conflict, such as vertigo, it becomes a conscious experience (Bles et al. 1980; Brandt et al. 1980). To reduce or eliminate such conditions arising adaptive mechanisms are involved (Norré 1990). In the presence of a conflict between visual, vestibular and proprioceptive inputs, the visual input normally dominates in the control of sway (Bronstein 1986), even though the fine sensory control of body sway is hierarchically organised.

The sensory inputs into the CNS are further processed to elicit various reflexes (ocular and spinal), as well as the voluntary control of posture.

• Ocular reflexes

Ocular reflexes underlie the first goal of maintaining postural balance by providing stabilisation of the visual field, whereby eye movements compensate for displacements of the head relative to the surroundings (Norré 1990).

Ocular reflexes comprise the optokinetic, vestibulo-ocular and cervico-ocular reflexes. The optokinetic reflex works on the basis of visual feeback maintaining a stable image when head movements are slow (Livingston 1990; Norré 1990; Purves et al. 1997). The reflex provides information about head movement relative to the environment, with the most important information coming via the peripheral retina (Norré 1990).

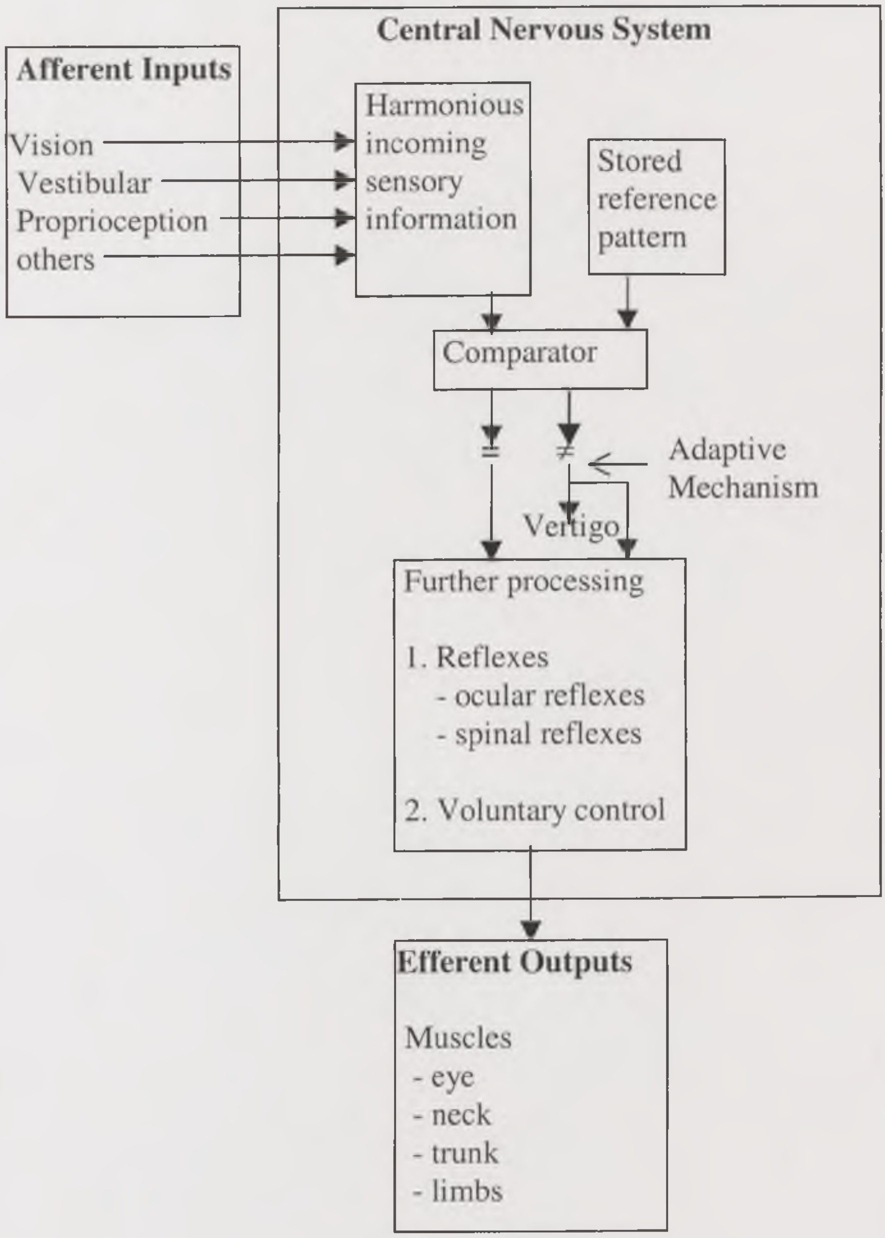


Figure 2.4 Central processing of sensory inputs (modified from Norré 1990).

The vestibulo-ocular reflex, a basic interaction between the visual and vestibular systems, maintains a stable image on the retina during rapid head rotation producing eye movements in the direction opposite and of equal amount to the head movement. Information from the semicircular canals is transmitted to the vestibular nuclei through the reticular formation and the medial longitudinal fasciculus to the extraocular motor nuclei and muscles. Thus, the vestibulo-ocular reflex operates to prevent head movement from disturbing retinal image stability (Livingston 1990; Purves et al. 1997). In normal subjects gaze stabilisation during head movements is compensated for almost completely by the vestibulo-ocular reflex (Barr et al. 1976). The optokinetic reflex reinforces the vestibulo-ocular reflex when vestibular information is insufficient to provide an adequate vestibulo-ocular reflex stabilising image on the retina during head movements, thus generating a reliable perception of self-motion in space (Zee et al. 1976). However, in labyrinthine function loss patients gaze stabilisation is a function of the cervico-ocular reflex, an interaction between visual and neck proprioceptive inputs (Kasai and Zee 1978). The proposed mechanism of this reflex is that neck receptors receive information about head movement with respect to the trunk, which is presumed to be transmitting through the vestibular nuclei, thereby generating an oppositely directed slow phase eye movement (Kasai and Zee 1978).

• Spinal reflexes

Spinal reflexes underlies the second goal of postural balance control, i.e. maintenance of the erect standing position involving both head and erect position stabilisation (Norré 1990).

Spinal reflexes comprise the vestobulocollic, vestibulospinal, cervicocollic and cervicospinal reflexes. The vestibulocollic reflex, as well as the cervicocollic reflex, contributes to head stabilisation in space and depends on voluntary control to supplement head stability compared to what it would be if the visual system was working alone (Guitton et al. 1986). The vestibulocollic reflex originates from the labyrinth, particularly from the semicircular canals. The infomation is transmitted to vestibular neurones via the medial vestibulospinal tract to act on the neck muscles (Guitton et al. 1986; Norré 1990; Purves et al. 1997). In contrast, the cervicocollic reflex is basically a neck stretch reflex translating information concerning neck displacement (Guitton et al. 1986; Norré 1990). It is the monosynaptic pathway linking muscle afferents to motoneurones of the same muscles (Norré 1990). Examination of subjects with tension neck indicates that the cervicocollic reflex controls the posture and activity of the neck muscles (Koskimies et al. 1997).

The vestibulospinal and cervicospinal reflexes provide head and body stabilisation. The vestibulospinal reflex has its origin in the vestibular system, particularly from the otoliths, sending information into the medial and lateral vestibulospinal tract to the spinal cord. This pathway mediates postural balance and the maintenance of upright posture by activating ipsilateral extensor muscles and inhibiting flexor muscles (Norré 1990; Purves et al. 1997). The cervicospinal reflex is activated by the change in angle between the head and neck with its effect being on the limbs (Roberts 1995). For head control the vestibulospinal and cervicospinal reflexes can substitute for each other in the absence of vestibular or neck inputs (Horak et al. 1992). The vestibulospinal reflex plays an integrating role accomplishing the automatic maintenance of the erect position by the appropriate adjustment of the body's muscles (Norré 1990).

Sensory input interaction

• Integrating areas

Several structures within the CNS are integrating areas for sensory inputs. The upper cervical spinal cord receives the vestibular and neck proprioceptive input and relays information to the cerebellum (Koskimies et al. 1997).

Nuclei in the brainstem integrate various sensory modalities. Vestibular nuclei are not only a relay station for vestibular information processing, but also act as an integration centre combining visual information with the vestibular input (Henn et al. 1974). Moreover, the convergence between limb/neck proprioception and vestibular input takes place in vestibular nuclei. Fifty-five percent of neurones in the caudal two thirds of the vestibular nuclear complex receive both semicircular canal and neck proprioceptive input (Anastasopoulos and Mergner 1982). Vestibular nucleus neurones receiving neck input project to the abducens nuclei, thus interacting with the vestibulo-ocular reflex (Hikosaka and Maeda 1973). Reticular formation cells, particularly medial reticular formation cells, also provide sensory integration, with vestibular cells responding to both contralateral and ipsilateral head movements, while auditory cells respond to visual stimuli moving in specific directions indicating a vestibular-neck proprioceptive interaction as well as visual-auditory combination occurs in the reticular formation (Siegel and Tomaszewski 1983). Most cerebellar regions receiving vestibular information also receives neck proprioceptor inputs (Norré 1990). An auditory-visual interaction has been shown to occur in the superior colliculus of primates (Lueck et al. 1990). Visual and neck proprioception appears to combine and influence tectospinal cells, whose origin are in the superior colliculus (Abrahams 1977).

In the thalamus 80% of ventroposterior thalamic neurones responding to vestibular stimulation showed convergence with joint and muscle proprioceptive input, with 60% of these neurones responding to neck proprioceptor input (Deecke et al. 1977). In addition, neck inputs to the ventromedial nucleus of the thalamus are directly influenced by vestibular inputs (Shinoda et al. 1992).

The cerebrum has recently been reported to be an integrating area for sensory inputs. The dorsolateral prefrontal cortex participates in the integration of auditory and visual inputs (Bodner et al. 1996). Additionally, in the lateral intraparietal area it is thought that the visual and auditory receptive and memory fields may overlap one another (Anderson et al. 1997). The parietal cortex integrates vestibular information with somatic sensory information (Martin, 1991) and with the visual system for self-motion perception (Brandt et al. 1998). Positron emission tomography has revealed visual-vestibular interaction during visually induced circularvection occuring in the medial parieto-occipital cortex, deep posterior insular and parieto-insular vestibular cortex (Brandt et al. 1998). Furthermore, the posterior parietal cortex combines visual, vestibular, proprioceptive and auditory signals in order to form spatial representation used to guide movements (Anderson et al. 1997).

• Visual-vestibular interaction

The interaction between visual and vestibular inputs subserves gaze stabilisation (Norré 1990), as well as object-motion and self-motion perception (Henn et al. 1974; Kolev et al. 1996; Brandt et al. 1998). Henn et al. (1974) demonstrated that the activity of vestibular units is consistently responsive to pure visual stimulation inducing circularvection: combined visual-vestibular stimulation shows a conflict between the two sensory systems. A non-linear interaction between visual and vestibular stimuli is demonstrated when the two are simultaneously applied. In addition, the estimation of self-motion by combining complementary visual and vestibular cues shows that low frequency visual cues are used to augment high-frequency vestibular cues. The extent of the visual-vestibular interaction appears to depend on the level of agreement between the visual and vestibular cues, with cue weighting being non-linear (Zacharias and Young 1981). Similarly, using positron emission tomography perception of self-motion can be dominated by either the vestibular or visual input. The interaction between visual and vestibular inputs is complex, depending not only on the pattern of visual motion stimulation but also on active postural and locomotor tasks. Deactivation of the visual cortex protects the vestibular system from conflicting visual motion input, while deactivation of the vestibular cortex prevents visually induced circularvection, suggesting that there is a shift of the dominant sensory weight from one modality to the other. Besides this reciprocal inhibitory interaction, the visual-vestibular cortices have other forms of interaction required for postural control in stimulus situations with unexpected, multidirectional transitions between body acceleration and motion at constant velocity (Brandt et al. 1998).

• Visual-neck proprioceptive interaction

The role of visual and neck proprioceptive inputs is described in the case of postural regulation in term of gaze direction. Neck muscle vibration induces visual illusions and a disturbance of pointing movement towards a target, suggesting that the alteration of neck proprioceptive input modified the body centred representation of visual space. Thus, a proprioceptive signal from the neck muscles has access to the mechanism calculating the direction of gaze (Biguer et al. 1988). The application of low amplitude mechanical vibrations to the inferior rectus of the eye or sternocleidomastoid of the neck induces a slow upward target displacement, whereas with trapezius and splenius muscle vibration there is a downward shift of the target. Simultaneous stimulation of the eye and neck muscles arises and summates to determine the target displacement (Roll et al. 1991). Vibration of the dorsal neck muscles leads to a falling reaction, which can be used as a reproducible error signal in analysing the interaction between neck and visual inputs, and is important for posture and eye-head movement coordination (Lund 1980). Wolsley et al. (1996) have demonstrated that the link between eye-in-orbit and head-on-trunk signals have the capacity to send visually evoked postural responses in different ways so that the appropriate postural muscles are activated.

• Visual-lower limb proprioceptive interaction

The effect of vision and stance distance, i.e. the distance between feet when parallel, on spontaneous body sway behaviour shows that the sway path, sway area, mediolateral and anteroposterior sway are diminished by visual feedback with smaller stance distances. Thus, visual control becomes more important when the feet are placed close together (Kollegger et al. 1989). The interaction between vision and stance width investigated by Day et al. (1993) indicated that vision reduces sway velocity more effectively when the feet are closer together. Nakagawa et al. (1993) also showed that when the eyes are closed the lateral and anteroposterior components of body sway are increased. The quotient of increasing body sway by vibration of the triceps surae of the both lower limbs, as well as visual suppression, shows that lower limb proprioception may have a minor role compared with vision and the disturbance of vision, with lower limb proprioceptive input appearing to be additive.

• Visual-auditory interaction

Studies have shown that there is a possibility that the combination of visual and auditory feedback can be used to voluntarily control posture (Takeya et al.

1976). The activity of single neurones recorded from the dorsolateral prefrontal cortex during the performance of an audio-visual short-term memory task indicates an interaction between visual and auditory information for the intended action (Bodner et al. 1996). Sakellari and Soames (1996) have demonstrated the interaction of specific auditory frequencies and vision on postural sway behaviour, showing that certain combinations of vision and sound lead to increased sway behaviour. The interaction between the visual and auditory systems appears to influence the programming of saccades, with the outcome of the interaction depending on the visual stimuli (Lueck et al. 1990).

• Vestibular and neck proprioceptive interaction

The interaction of vestibular and neck proprioceptive inputs has been observed to be linearly integrated (Anastasopoulos and Mergner 1982; Karnath et al. 1994). Recording neurone activities in the vestibular nuclear complex under conditions of muscle relaxation shows that combined labyrinth and neck stimulation results in their addition with synergistic convergence but substraction with antagonistic convergence. This finding suggests that the labyrinthine-neck interaction may be involved in postural control (Anastasopoulos and Mergner 1982). Karnath et al. (1994) later showed that the combination of posterior neck muscle vibration and caloric vestibular stimulation leads to a horizontal deviation of subjective body orientation when either type of stimulation is applied and is linearly combined either by summation or by cancellation. The vestibular-neck combination provides information regarding head rotation in space by the vestibular signalling of head in space orientation creating an internal representation of the trunk in space, which then combines with the closely matching neck signal of head on trunk (Mergner et al. 1991). This combination also informs about trunk motion in space by the head being referred to trunk coordinates, while the trunk is referred to space coordinates (Mergner et al. 1991). In addition, the interaction between vestibular and neck inputs leads to object motion in space. During vestibular and neck muscle stimulation subjects experience a visual movement of a stationary target (Karnath et al. 1994). Mergner et al. (1992) believe that the perception of object motion in space is derived from the superposition of three signals representing object to head, head on trunk and trunk in space relationships.

• Vestibular and lower limb proprioception interaction

The integration of vestibular and lower limb proprioception may be important in the perception of the body in space, body acceleration and for controlling body movement (Martin 1991). Recordings of tibialis anterior and soleus muscle activity shows an increase in amplitude when standing on an unstable support surface with the eyes closed, indicating that posture depends on vestibular input when lower limb proprioceptive input is unreliable (Fitzpatrick et al. 1994a). Vestibular stimulation delivered before and continuously during the platform translation produced larger changes during the execution of the postural movement and in the final equilibrium position than during quiet stance (Inglis et al. 1995). This finding shows that the lower limb information during body motion shapes initial postural responses while the vestibular signals modulate the amplitude of these responses. This is consistent with the idea of the integration of somatosensory and vestibular signals improving the sensitivity of the CNS's estimate of body motion.

2.2.3 Efferent output

Effective efferent output is necessary for adequate postural control and stability, requiring cooperation between the neck, trunk and limb muscles. The elderly have a larger sway area than do the young (Hasselkus and Shambes. 1975), probably due to weaker muscle strength in the elderly (Toupet et al. 1992). In right hemiparesis patients, for example, the COP is shifted away from the disabled limbs during standing, indicating lesser weight-supporting activity (Murray et al. 1975). Patients with Parkinson's disease also show greater amplitude of postural sway than healthy subjects (Njikoktjien and De Rijke 1972).

Chapter 3
Materials and methods

3.1 Postural sway behaviour recording

Postural way behaviour under various experimental conditions, while standing upright without shoes and feet together, was recorded using an AMTI biomechanics force measuring platform (details are given in Appendix 1) directly connected to an amplifier and computer (Figure 3.1).

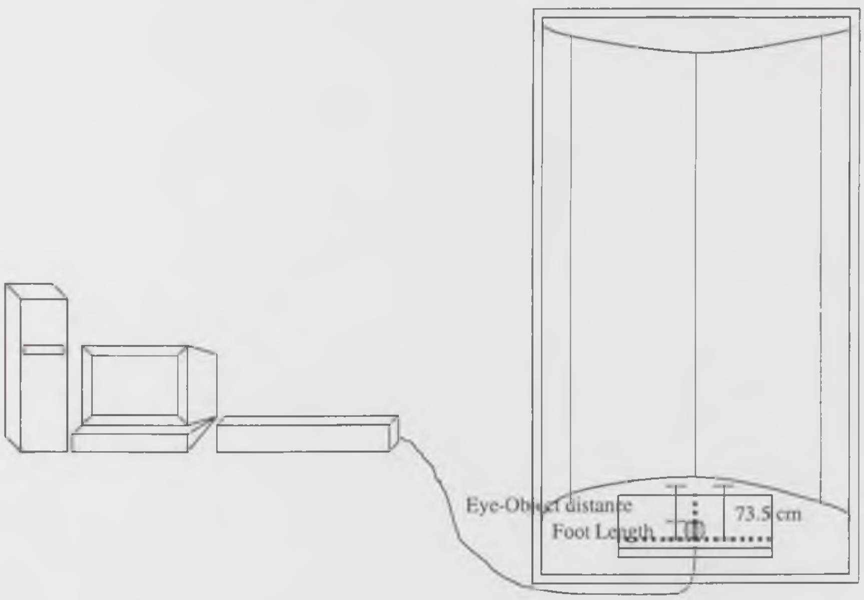


Figure 3.1 The connection of the force measuring platform to an amplifier and computer. The platform centre, which is the placement point of the heel, is 73.5cm from the specially constructed screen with faint centre, right and left vertical lines placed around three side of the platform.

3.2 Data acquisition and storage

The analogue data from the amplifier were acquired and stored using specially written software based on DT VEE (details are given in Appendix 2). The stored data was downloaded into Microsoft Excel for subsequent analysis.

3.3 Postural sway parameters

Further software, based on DT VEE, was written to enable the calculation of specific postural sway parameter from each individual recording of postural sway behaviour:

- the mean centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions: the axis of the ankle joint was aligned with the mediolateral axis of the platform [the unit in Chapters 4-11 should read centimetre (cm) rather than millimetre (mm)]
- the magnitude of mediolateral sway (Sx), including sway separately to the right (Sr) and left (Sl), and anteroposterior sway (Sy), including sway separately anteriorly (Sa) and posteriorly (Sp) [in Chapter 4 these values are expressed in millimetres (mm), while in Chapters 5-11 the unit should read centimetre (cm) rather than millimetre (mm)]
- the total path length of COG movement (TL), including separate movement in the mediolateral (TLx) and anteroposterior (TLy) directions
- the mean sway velocity (Vm), including the separate velocities in the mediolateral (Vxm) and anteroposterior (Vym) directions
- the angle of sway with respect to the sagittal plane (Ay), clockwise being positive.

3.4 Data analysis

Analysis of variance was conducted for each sway parameter with vision, neck rotation, neck flexion/extension, sound and sex as independent variables in order to determine the influence of each on postural sway. t-tests were conducted to determine any significant differences where appropriate.

3.5 Constructed screen

As shown in Figure 3.1 a specially constructed curved screen was placed around the platform: the centre of the force platform being 73.5 centimetres (cm) from the screen. Except for three narrow faint vertical lines, the centre vertical line being aligned with respect to the anteroposterior axis of the platform with the remaining two lines placed to produced 45^0 neck rotation to the right and left, all vertical and horizontal cues were eliminated.

3.6 Subjects

Volunteers aged between 18 and 43 years, all of whom were healthy and had no history of visual, vestibular, neck and auditory problems or defects, agreed to participate in the studies. Prior to testing each subject had refrained from eating, drinking and smoking for at least one hour. Subject's height, eye level above the ground, taken to the left lateral canthus, and left foot length were measured to enable the calculation of 45^0 neck flexion and extension.

Fifty-eight healthy volunteers (28 females, 30 males) participated in the first experiment, in which postural sway behaviour in response to static visual, vestibular and neck proprioceptive stimulation was examined. Thirty healthy volunteers (15 females, 15 males) participated in each of the next three experiments: experiment 2 investigated postural sway behaviour in response to dynamic vestibular and neck proprioceptive stimulation while follow a moving visual target: experiment 3 examined postural sway behaviour in response to static visual, vestibular, neck proprioceptive and auditory stimulation: and finally experiment 4 examined postural sway behaviour in response to dynamic vestibular and neck proprioceptive stimulation with auditory stimulation while the following a moving visual target.

Sixteen subjects (9 females, 7 males) participated in both experiment 1 and 2, twenty-one (12 females, 9 males) in both experiment 1 and 3, twenty-two (12 females, 10 males) in both experiment 2 and 4, and thirty subjects (15 females, 15 males) in both experiment 3 and 4. This enabled comparisons to be made between the different experimental conditions.

3.7 Experimental methods

3.7.1 Experiment 1: Responses to static visual, vestibular and neck proprioceptor stimulation

A single marker was placed in turn on the points shown on the screen (Figure 3.2). The marker placement being in positions that would achieve specific combinations of head and neck postures. Trigonometry was used to determine marker placement to achieve 45^0 neck flexion or extension for each subject as shown in Figure 3.3.

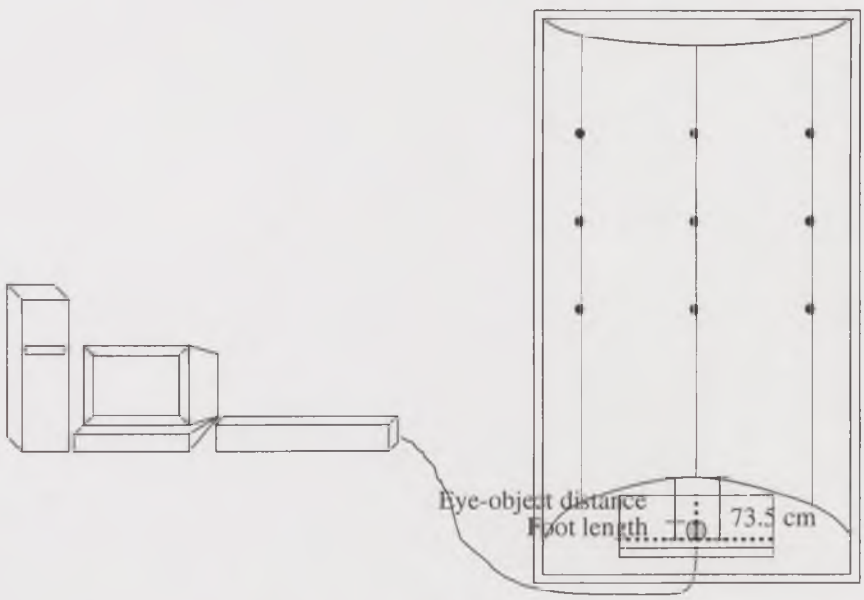


Figure 3.2 The sites of marker placement used in Experiment 1.

The various experimental conditions investigated were combinations of visual, vestibular and static neck positions. Subjects either looked directly ahead (A), or to the side with the neck rotated 45^0 to the right (R) or left (L), each with the neck in a neutral (N), flexed (F) or extended (E) 45^0 with the eyes open (O) or closed (C): in total 18 different combinations were tested. For each test combination postural sway behaviour was recorded for 20 seconds between which subjects were allowed to relax on the platform but not move their feet. When instructed subjects were told to focus on the specific marker on the screen following which the recording of postural sway was taken. To minimise the effects of fatigue a two-minute rest period was incorporated between each set of three recordings during which time subjects were permitted to sit down. The sequence in which the various combinations were presented to subjects was randomised to reduce the possibility of 'carry-over' effects.

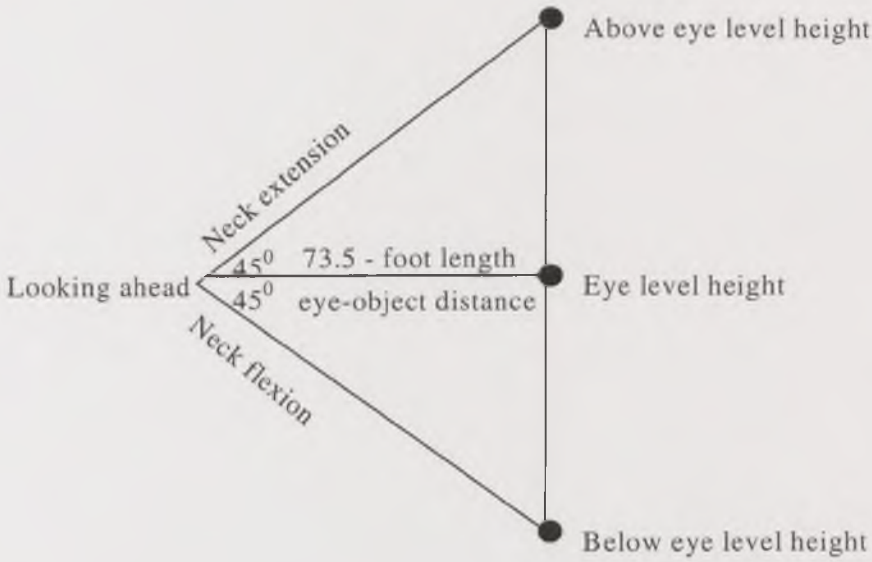


Figure 3.3 The placement of markers to achieve 45^0 flexion or extension and looking ahead.

3.7.2 Experiment 2: Responses to dynamic vestibular and neck proprioceptor stimulation while visually tracking a moving target

In a darkened room, a spot of light was projected onto the screen (details are given in Appendix 3) and moved in various directions at either of two velocities, 0.2m/s and 1.0m/s (0.1Hz and 0.5Hz: the path length of movement was 2 metres). The extent of neck flexion/extension was calculated as shown in Figure 3.3. The target moved continuously either horizontally with the neck flexed (F) or extended (E) 45^0 or in neutral (N) between 45^0 neck rotation to the right and left (Figure 3.4a), or vertically along each of three vertical lines on the screen, which when viewed by subjects resulted in flexion and extension of the neck while looking ahead (A) and with the neck rotated 45^0 neck rotation either to the right (R) or left (L) (Figure 3.4b), or moving diagonally from either the right to left (RE) or left to right (LE), which when viewed by subjects resulted in continuous involvement of both neck rotation and flexion/extension (Figure 3.4c): in total 16 different combinations were tested, each for 20 seconds. When instructed subjects wore goggles which restricted their visual field to the central visual field, and were told to follow the moving target on the screen. To minimise the effect of fatigue a five-minute rest period was incorporated between each set of tests (velocity of movement 0.2m/s and velocity of movement 1.0m/s) during which time subjects were permitted to sit down.

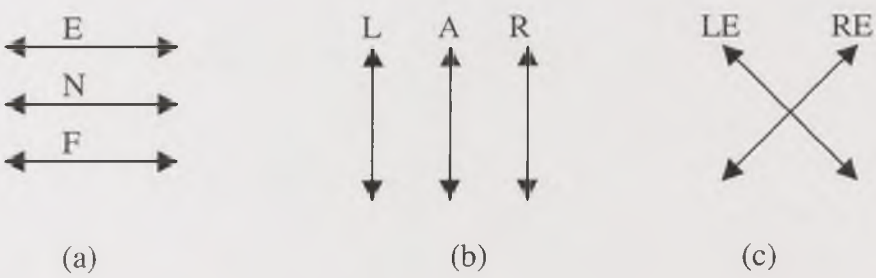


Figure 3.4 **The direction of head movement (a) horizontally with 45^0 neck flexion (F), 45^0 extension (E) or neutral (N), (b) vertically with 45^0 neck rotation either to the right (R) or left (L) or looking ahead (A), (c) diagonally with neck rotation to the right and extended moving to the left and flexed (RE) or neck rotation to the left and extended moving to the right and flexed (LE).**

3.7.3 Experiment 3: Responses to static visual, vestibular, neck proprioceptor and auditory stimulation

In addition to the method employed in Experiment 1 (Chapter 3 part 3.7.1) an 80dB sound at either 1595Hz or 2916Hz was added (further details are given in Appendix 4). These frequencies were chosen on the basis of the findings of Sakellari and Soames (1996) in which 1595Hz was found to have a stabilising effect, while 2916Hz had a destabilising effect on the upright posture.

Focusing on a specific marker on the screen was the same as in experiment 1, but in addition the sound was transmitted through the headphones: in total 36 different combinations were tested each for 20 seconds. To minimise the effect of fatigue and accommodation to the sound a rest period was incorporated between each set of tests (eyes open at 1595Hz, eyes closed at 1595Hz, eyes open at 2916Hz and eyes closed at 2916Hz).

3.7.4 Experiment 4: Responses to dynamic vestibular and neck proprioceptor stimulation with auditory stimulation while visually tracking a moving target

In addition to the method employed in Experiment 2 (Chapter 3 part 3.7.2) sounds of similar loudness and frequency as in experiment 3 were added in this experiment. While following the moving target the sound was transmitted through the headphone: in total 32 different combinations were tested each for 20 seconds. To minimise the effect of fatigue and accommodation to the sound a rest period was incorporated between each set of tests (velocity of movement with sound frequency: 0.2m/s with 1595Hz, 0.2m/s with 2916Hz, 1.0m/s with 1595Hz and 1.0m/s with 2916Hz).

Chapter 4

Experiment 1: Responses to static visual, vestibular and neck proprioceptor stimulation

4.1 Introduction

The maintenance of posture is controlled by sensory systems principally the visual (Gantchev et al. 1981; Paulus et al. 1984; Kollegger et al. 1992), vestibular (Njiokiktjien and De Rijke 1972; Keshner et al. 1987; Horak et al. 1990) and proprioceptive systems (Abrahams 1977; Manzoni et al. 1979; Lund 1980; Horak and Nashner 1986; Biguer et al. 1988; Dietz et al. 1988; Magnusson et al. 1990; Nakagawa et al. 1993; Koskimies et al. 1997). In addition to lower limb proprioception the neck proproceptive system has also been reported to play a role in postural control in man (Lund 1980; Biguer et al. 1988; Smetanin et al. 1993; Koskimies et al. 1997). The interaction and integration between the inputs of any two sensory systems (visual-vestibular, visual-neck proprioception, vestibular-neck proprioception) occurs in the brain (Henn et al. 1974; Anastaspoulos and Mergner 1982; Shinoda et al. 1992) with their summation being important for the perception of object-motion, self-motion (Kolev et al. 1996; Brandt et al. 1998) or trunk-motion (Mergner et al. 1991), as well as for the determination of target displacement (Roll et al. 1991). Combinations of these various inputs achieves the goal of postural maintenance and control. Thus, in this experiment both the individual and interaction of visual, vestibular and neck proprioceptor stimulation, particularly in response to static head stimulation on postural sway behaviour, is investigated.

4.2 Materials and methods

Fifty-eight healthy subjects (28 females, 30 males), aged between 18 and 32 years, participated in the experiment.

Measurements were obtained from a total of 18 test conditions. Three recordings of each being taken: looking directly ahead (A), neck rotated 45^0 to the right (R) and left (L), each with the neck in neutral (N), 45^0 of flexion (F) or 45^0 extension (E) and with the eyes open (O) and closed (C) for each subject. The recordings of postural sway behaviour were taken with the subject standing comfortably erect with the feet together on the force platform after they had been instructed to look at and focus on a specific marker placed on the screen (for further details see Chapter 3 part 3.7.1).

Four-way analyses of variance were conducted on each of the sway parameters (Chapter 3 part 3.3) with sex, vision, neck rotation (looking ahead/right/left) and neck flexion/extension (neutral/flexion/extension) as independent variables in order to determine the influence of each on postural sway behaviour. t-tests were conducted as appropriate to determine the differences in each group of independent variables influencing each postural sway parameter. In addition, t-tests were conducted for subject characteristics. Unless otherwise stated all differences are at the 5% level of significance.

4.3 Results

4.3.1 Subject characteristics

The characteristics of the population studied are given in Table 4.1, with the data being presented for the whole group, as well as for females and males separately. There was no difference in age between females and males, however height, foot length and eye level height were significantly ($p<0.01$) greater and eye-object distance significantly ($p<0.01$) smaller in males.

Subject characteristics	All	Females	Males
Age (year)	23.5 ± 3.89	23.9 ± 3.58	23.0 ± 4.18
Height (cm)	168.6 ± 10.05	162.3 ± 8.14	174.5 ± 7.87 **
Foot length (cm)	25.4 ± 2.02	24.0 ± 1.19	26.8 ± 1.68 **
Eye-Object distance (cm)	48.1 ± 2.02	49.5 ± 1.32	46.8 ± 1.68 **
Eye level height (cm)	158.6 ± 9.55	152.5 ± 6.94	164.3 ± 8.05 **

**significantly ($p<0.01$) greater or less than female value.

Table 4.1 The characteristics of the subjects (28 females, 30 males) who participated in Experiment 1 (mean ± SD).

4.3.2 Analyses of variance

The results of the various analyses of variance are presented in Appendix 5, showing sex, vision, neck rotation, neck flexion/extension as well as their interactions on the various parameters of postural sway behaviour.

Sex

Few differences in sway behaviour were observed between females and males, the differences being restricted to TL, TLx, Vm and Vxm, which were all significantly greater ($p<0.01$) in females (TL, 94.8 ± 15.7; TLx, 58.9 ± 11.1; Vm, 4.74 ± 0.79; Vxm, 2.95 ± 0.56) than males (TL, 87.0 ± 18.1; TLx, 53.4 ± 12.1; Vm, 4.35 ± 0.91; Vxm, 2.67 ± 0.60).

Vision

The loss of vision, i.e. standing with eyes closed, influenced most postural sway parameters. As shown in Table 4.2 when standing with the eyes closed the mean COG projection (X, Y) moved significantly more to the right and posteriorly ($p<0.01$). In addition, the mean magnitude of mediolateral and anteroposterior sway significantly ($p<0.01$) increased when standing with eyes closed. The total path length and the mean velocity of sway, including those in the mediolateral and anteroposterior directions separately, also significantly ($p<0.01$) increased with loss of visual feedback. The only sway parameter not influenced by the loss of vision was Ay.

Postural sway parameter	Vision	
	Eyes open	Eyes closed
X (mm)	1.53 ± 2.34	1.62 ± 2.34 *
Y (mm)	1.79 ± 2.01	1.68 ± 1.99 **
Sx (mm)	6.40 ± 2.22	9.96 ± 3.94 **
Sr (mm)	3.19 ± 1.10	4.97 ± 1.98 **
Sl (mm)	3.23 ± 1.16	4.99 ± 1.98 **
Sy (mm)	5.34 ± 1.81	8.02 ± 3.23 **
Sa (mm)	2.68 ± 0.92	3.98 ± 1.60 **
Sp (mm)	2.67 ± 0.93	4.03 ± 1.65 **
TL (mm)	84.4 ± 12.8	97.1 ± 19.4 **
TLx (mm)	51.5 ± 8.40	60.6 ± 13.2 **
TLy (mm)	53.4 ± 8.35	60.8 ± 12.4 **
Vm (mm/s)	4.22 ± 0.64	4.86 ± 0.97 **
Vxm (mm/s)	2.58 ± 0.42	3.03 ± 0.66 **
Vym (mm/s)	2.67 ± 0.43	3.04 ± 0.62 **
Ay (°)	28.1 ± 40.0	26.6 ± 37.2

* $p<0.05$, ** $p<0.01$ significantly greater or less than eyes open.

Table 4.2 The influence of vision on the centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions, magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), total path length (TL), mediolateral (TLx) and anteroposterior (TLy) path lengths, mean velocity of sway (Vm), mediolateral (Vxm) and anteroposterior (Vym) sway velocities, and angle of sway from the sagittal plane (Ay) (mean ± SD).

Neck rotation

Neck rotation, both to the right and left, had a significant influence on Y, Sx, Sr, Sy, Sa and Ay. As shown in Table 4.3 neck rotation to the right and left significantly ($p<0.01$) shifted the COG projection posteriorly compared to looking directly ahead, whereas there was no effect on the mediolateral COG projection. Neck rotation also significantly ($p<0.01$) increased Sx and Sy. The increase in Sx is due to an increase in Sr, with Sl remaining unchanged, whereas the increase in Sy is due to an increase in Sa with Sp remaining unchanged. Neck rotation significantly decreased Ay.

Postural sway parameter	Neck rotation		
	Left	Looking ahead	Right
X (mm)	1.52 ± 2.52	1.70 ± 2.19	1.68 ± 2.30
Y (mm)	1.69 ± 2.01 **	1.87 ± 2.07	1.70 ± 1.93 **
Sx (mm)	8.54 ± 3.53 **	7.90 ± 3.67	8.33 ± 3.77 **
Sr (mm)	4.28 ± 1.79 **	3.95 ± 1.83	4.14 ± 1.88 **
Sl (mm)	4.27 ± 1.78	3.99 ± 1.86	4.18 ± 1.90
Sy (mm)	6.93 ± 2.96 **	6.52 ± 2.88	6.77 ± 2.98 **
Sa (mm)	3.45 ± 1.49 **	3.24 ± 1.42	3.37 ± 1.47 **
Sp (mm)	3.47 ± 1.50	3.29 ± 1.51	3.38 ± 1.49
Ay (^{o})	25.8 ± 42.0 **	30.2 ± 34.5	29.00 ± 38.7 **

** significantly ($p<0.01$) greater or less than looking directly ahead.

Table 4.3 **The influence of neck rotation on the centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions, magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), and angle of sway from the sagittal plane (Ay) (mean ± SD).**

Neck flexion/extension

Neck flexion/extension had a significant influence on most sway behaviour parameters: further analysis showed that it was the neck extended posture which was responsible for the majority of differences observed. As shown in Table 4.4 both neck flexion and extension resulted in a significant ($p<0.01$) posterior shift of the mean anteroposterior COG projection compared with the neck in neutral; no difference was observed between neck extension and flexion. Neck extension significantly ($p<0.01$) increased Sx, Sr and Sl compared with neck in neutral, whereas neck flexion increased Sx when compared to the neck in neutral, being accounted for by an increase in Sr. In contrast, neck flexion did not influence Sy, Sa and Sp, however neck extension increased Sy, Sa and Sp compared with the neck in neutral or flexed. Similarly, neck extension was observed to increase TL, TLx and TLy, as well as Vm, Vxm and Vym compared with the neck in neutral or flexed. Ay was not influenced by neck flexion/extension.

Postural sway parameter	Neck flexion/extension		
	Extension	Neutral	Flexion
X (mm)	1.60 ± 2.29	1.50 ± 2.44	1.63 ± 2.29
Y (mm)	1.68 ± 2.00 **	1.82 ± 2.00	1.71 ± 2.01 **
Sx (mm)	8.36 ± 3.92 **	7.96 ± 3.48	8.22 ± 3.56 *
Sr (mm)	4.18 ± 1.97 **	3.97 ± 1.75	4.10 ± 1.78 *
Sl (mm)	4.20 ± 1.98 **	4.01 ± 1.75	4.12 ± 1.81
Sy (mm)	6.95 ± 3.15 ++	6.47 ± 2.81	6.62 ± 2.84
Sa (mm)	3.47 ± 1.57 ++	3.24 ± 1.41	3.28 ± 1.39
Sp (mm)	3.50 ± 1.63 ++	3.24 ± 1.42	3.31 ± 1.43
TL (mm)	91.8 ± 18.3 ++	90.4 ± 17.6	90.2 ± 16.9
TLx (mm)	56.7 ± 12.4 ++	55.7 ± 12.1	55.7 ± 11.3
Tly (mm)	57.8 ± 11.6 ++	56.9 ± 11.1	56.7 ± 10.9
Vm (mm/s)	4.59 ± 0.91 ++	4.52 ± 0.88	4.51 ± 0.84
Vxm (mm/s)	2.84 ± 0.62 ++	2.79 ± 0.60	2.79 ± 0.57
Vym (mm/s)	2.89 ± 0.58 ++	2.84 ± 0.57	2.84 ± 0.54
Ay (°)	27.6 ± 38.4	26.3 ± 38.7	28.2 ± 38.9

* $p<0.05$, ** $p<0.01$ significantly greater or less than neutral.
++ significantly ($p<0.01$) greater than neutral and flexion.

Table 4.4 The influence of neck flexion/extension on the centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions, magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), total path length (TL), mediolateral (TLx) and anteroposterior (TLy) path lengths, mean velocity of sway (Vm), mediolateral (Vxm) and anteroposterior (Vym) sway velocities, and angle of sway from the sagittal plane (Ay) (mean ± SD).

Interaction between vision and neck rotation

There was a significant interaction between vision and neck rotation for most postural sway parameters. As shown in Table 4.5 there was no significant difference in the mean mediolateral COG projection for any neck position either with or without visual feedback. In contrast, there was significant posterior shift in

Eyes Open

Postural sway parameter	Neck rotation		
	Left	Looking ahead	Right
X (mm)	1.32 ± 2.58	1.64 ± 2.12	1.64 ± 2.30
Y (mm)	1.69 ± 2.00 **	1.95 ± 2.09	1.73 ± 1.94 **
Sx (mm)	6.79 ± 2.31 **	5.85 ± 2.09	6.56 ± 2.16 **
Sr (mm)	3.42 ± 1.23 **	2.91 ± 0.97	3.24 ± 1.03 **
Sl (mm)	3.39 ± 1.16 **	2.98 ± 1.16	3.32 ± 1.14 **
Sy (mm)	5.58 ± 1.94 **	5.07 ± 1.78	5.38 ± 1.68 **
Sa (mm)	2.80 ± 0.99 **	2.54 ± 0.93	2.68 ± 0.84 **
Sp (mm)	2.79 ± 0.98 **	2.54 ± 0.93	2.69 ± 0.85 **
TL (mm)	85.3 ± 13.1 **	83.2 ± 12.5	84.8 ± 12.8 **
TLx (mm)	52.3 ± 8.38 **	50.4 ± 8.27	51.9 ± 8.47 **
Tly (mm)	53.7 ± 8.85	53.0 ± 8.01	53.5 ± 8.19
Vm (mm/s)	4.26 ± 0.65 **	4.16 ± 0.63	4.24 ± 0.64 **
Vxm (mm/s)	2.62 ± 0.42 **	2.52 ± 0.41	2.60 ± 0.42 **
Vym (mm/s)	2.69 ± 0.44	2.64 ± 0.44	2.68 ± 0.41
Ay (°)	23.2 ± 44.8	31.3 ± 34.6	29.9 ± 39.9

** significantly ($p<0.01$) greater or less than looking directly ahead.

Eyes Closed

Postural sway parameter	Neck Rotation		
	Left	Looking ahead	Right
X (mm)	1.38 ± 2.46	1.76 ± 2.26	1.71 ± 2.30
Y (mm)	1.60 ± 2.02 **	1.79 ± 2.04	1.66 ± 1.93 *
Sx (mm)	9.83 ± 3.87	9.95 ± 3.77	10.09 ± 4.20
Sr (mm)	4.90 ± 1.95	4.99 ± 1.90	5.03 ± 2.10
Sl (mm)	4.93 ± 1.95	4.99 ± 1.89	5.04 ± 2.11
Sy (mm)	7.94 ± 3.33	7.96 ± 3.04	8.17 ± 3.34
Sa (mm)	3.95 ± 1.68	3.93 ± 1.49	4.06 ± 1.63
Sp (mm)	3.98 ± 1.68	4.03 ± 1.61	4.07 ± 1.66
TL (mm)	96.1 ± 18.6	98.0 ± 19.0	97.2 ± 20.5
TLx (mm)	59.9 ± 12.3	61.3 ± 13.1	60.7 ± 14.1
Tly (mm)	60.3 ± 12.4	61.4 ± 12.1	60.8 ± 12.7
Vm (mm/s)	4.81 ± 0.93	4.90 ± 0.95	4.86 ± 1.02
Vxm (mm/s)	2.99 ± 0.61	3.06 ± 0.66	3.03 ± 0.70
Vym (mm/s)	3.01 ± 0.62	3.07 ± 0.60	3.04 ± 0.64
Ay (°)	22.6 ± 39.3	29.1 ± 34.5	28.1 ± 37.5

* $p<0.05$, ** $p<0.01$ significantly less than looking directly ahead.

Table 4.5 **The interaction between vision and neck rotation on the centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions, magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), total path length (TL), mediolateral (TLx) and anteroposterior (TLy) path lengths, mean velocity of sway (Vm), mediolateral (Vxm) and anteroposterior (Vym) sway velocities, and angle of sway from the sagittal plane (Ay) (mean ± SD).**

the mean COG projection when standing with the neck rotated to the right or left compared with looking directly ahead, both with and without visual feedback. Both Sx and Sy were significantly ($p<0.01$) increased when standing with the eyes open and the neck rotated compared with looking directly ahead. However, without visual feedback no significant differences in sway magnitude were observed. When considered separately both Sr and Sl, and Sa and Sp, with visual feedback, showed a significant ($p<0.01$) increase in sway magnitude with neck rotation compared with looking directly ahead. Again without visual feedback no differences in sway magnitude were observed. With visual feedback TL and Vm were also significantly ($p<0.01$) increased with neck rotation compared with looking directly ahead. These increases were due to significant ($p<0.01$) increases in TLx and Vxm respectively. Without vision no significant differences in the path length and velocity of sway in both the mediolateral and anteroposterior directions were observed. Ay was not influenced by the interaction between vision and neck rotation.

Interaction between vision and neck flexion/extension

The analyses of variance showed significant interactions between vision and neck flexion/extension for most postural sway parameters. As shown in Table 4.6 there was no significant difference in the mean mediolateral COG projection, however a significant ($p<0.01$) posterior shift was observed when standing with the neck extended or flexed compared with neutral, both with and without visual feedback. Standing with the eyes open Sx and Sy, including Sr, Sl, Sa and Sp, all significantly ($p<0.01$) increased in magnitude with the neck flexed compared with the neck in neutral, but without visual feedback sway magnitude was significantly ($p<0.01$) increased with the neck extended compared with the neutral or flexed posture. TL and Vm were also significantly ($p<0.01$) increased with the neck extended compared with neutral and flexion when standing without visual feedback. Similarly, without visual feedback TLx, TLy, Vxm and Vym significantly increased when the neck was extended compared with neutral and flexion. With visual feedback there was no significant difference in path length or

Eyes Open

Postural sway parameter	Neck flexion/extension		
	Extension	Neutral	Flexion
X (mm)	1.57 ± 2.31	1.48 ± 2.40	1.55 ± 2.32
Y (mm)	1.76 ± 2.00 **	1.89 ± 2.02	1.73 ± 2.03 **
Sx (mm)	6.35 ± 2.27	6.24 ± 2.16	6.62 ± 2.22 **
Sr (mm)	3.17 ± 1.09	3.11 ± 1.10	3.29 ± 1.11 **
Sl (mm)	3.21 ± 1.24	3.15 ± 1.07	3.33 ± 1.19 **
Sy (mm)	5.36 ± 1.89	5.16 ± 1.78	5.50 ± 1.76 **
Sa (mm)	2.69 ± 0.97	2.59 ± 0.89	2.75 ± 0.91 **
Sp (mm)	2.70 ± 1.00	2.58 ± 0.90	2.74 ± 0.87 **
TL (mm)	84.5 ± 13.0	84.1 ± 12.9	84.7 ± 12.6
TLx (mm)	51.6 ± 8.54	51.3 ± 8.54	51.7 ± 8.15
Tly (mm)	53.5 ± 8.42	53.3 ± 8.37	53.5 ± 8.30
Vm (mm/s)	4.23 ± 0.65	4.21 ± 0.65	4.23 ± 0.63
Vxm (mm/s)	2.58 ± 0.43	2.56 ± 0.43	2.59 ± 0.41
Vym (mm/s)	2.67 ± 0.42	2.66 ± 0.46	2.67 ± 0.42
Ay (°)	28.0 ± 40.3	27.1 ± 39.5	29.3 ± 40.5

** significantly ($p<0.01$) greater or less than neutral.

Eyes Closed

Postural sway parameter	Neck flexion/extension		
	Extension	Neutral	Flexion
X (mm)	1.63 ± 2.28	1.52 ± 2.48	1.71 ± 2.28
Y (mm)	1.60 ± 2.00 **	1.76 ± 1.99	1.69 ± 2.00 **
Sx (mm)	10.4 ± 4.19 ++	9.68 ± 3.71	9.83 ± 3.91
Sr (mm)	5.19 ± 2.12 ++	4.82 ± 1.86	4.90 ± 1.94
Sl (mm)	5.19 ± 2.09 ++	4.86 ± 1.88	4.91 ± 1.98
Sy (mm)	8.54 ± 3.36 ++	7.78 ± 3.04	7.74 ± 3.25
Sa (mm)	4.25 ± 1.66 ++	3.89 ± 1.52	3.81 ± 1.58
Sp (mm)	4.31 ± 1.73 ++	3.90 ± 1.54	3.88 ± 1.64
TL (mm)	99.1 ± 19.9 ++	96.6 ± 19.4	95.8 ± 18.7
TLx (mm)	61.9 ± 13.5 ++	60.2 ± 13.4	59.7 ± 12.6
TLy (mm)	62.1 ± 12.7 ++	60.4 ± 12.2	59.9 ± 12.1
Vm (mm/sec)	4.95 ± 0.99 ++	4.83 ± 0.97	4.79 ± 0.94
Vxm (mm/sec)	3.10 ± 0.67 ++	3.01 ± 0.67	2.98 ± 0.63
Vym (mm/sec)	3.10 ± 0.64 ++	3.02 ± 0.61	3.00 ± 0.61
Ay (°)	27.3 ± 36.5	25.5 ± 38.0	27.1 ± 37.2

** significantly ($p<0.01$) less than neutral.
++ significantly ($p<0.01$) greater than neutral and flexion.

Table 4.6 **The interaction between vision and neck flexion/extension on the centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions, magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), total path length (TL), mediolateral (TLx) and anteroposterior (TLy) path lengths, mean velocity of sway (Vm), mediolateral (Vxm) and anteroposterior (Vym) sway velocities, and angle of sway from the sagittal plane (Ay) (mean ± SD).**

the velocity of sway in both the mediolateral and anteroposterior directions. Ay was not influenced by any interaction between vision and neck flexion/extension.

Interaction between sex, vision and neck flexion/extension

The only significant interaction between sex, vision and neck flexion/extension was observed for the mean COG projection in the mediolateral direction and the mediolateral sway magnitudes. Table 4.7 shows a significant ($p<0.01$) left shift in the COG projection with the neck extended compared with flexion with visual feedback for males: no differences were observed irrespective of neck posture without feedback in both males and females. There was a significant ($p<0.01$) increase in Sx, Sr and Sl in females with neck flexion compared with neutral with visual feedback, but no difference without visual feedback. For males there was a significant ($p<0.01$) decrease in Sx, Sr and Sl with the neck extended compared with flexion with visual feedback, but an increase with extension compared with neutral and flexion without visual feedback.

Interaction between neck rotation and neck flexion/extension

The analyses of variance revealed that only those parameters associated with anteroposterior sway showed a significant interaction between neck rotation and neck flexion/extension. As shown in Table 4.8 when looking directly ahead the mean COG projection was further posteriorly with the neck flexed or extended than with the neck in neutral. There was a significant ($p<0.01$) increase in Sy, Sa and Sp when looking directly ahead or with the neck rotated to the right, both with the neck extended, but not with neutral or flexion. No difference was observed with the neck rotated to the left. For TLy and Vym there was a significant increase with neck rotation to the left when flexed compared with neutral, whereas with rotation to the right or looking directly ahead there was a significant increase in TLy and Vym with neck extension compared with flexion.

Interaction between sex, neck rotation and neck flexion/extension

The only significant interaction was for Y. In females there was a significant (p<0.01) posterior shift of the COG projection when the neck was rotated to the left or looking directly ahead with extension compared with neutral (Table 4.9). However, for males there was posterior shift of the COG projection when looking directly ahead with extension or flexion compared neutral (Table 4.9).

Females

Postural sway parameter	Vision	Neck flexion/extension		
		Extension	Neutral	Flexion
X (mm)	Eyes open	1.68 ± 2.79	1.46 ± 2.91	1.43 ± 2.81
	Eyes closed	1.60 ± 2.73	1.57 ± 3.06	1.79 ± 2.73
Sx (mm)	Eyes open	6.66 ± 2.31	6.25 ± 1.89	6.71 ± 2.06 **
	Eyes closed	10.3 ± 3.80	10.0 ± 3.49	10.0 ± 3.98
Sr (mm)	Eyes open	3.32 ± 1.06	3.12 ± 0.99	3.31 ± 0.96 **
	Eyes closed	5.17 ± 1.92	5.01 ± 1.81	4.99 ± 1.99
Sl (mm)	Eyes open	3.39 ± 1.33	3.18 ± 0.95	3.39 ± 1.12 **
	Eyes closed	5.19 ± 1.90	5.02 ± 1.72	5.06 ± 2.03

** significantly (p<0.01) greater than neutral.

Males

Postural sway parameter	Vision	Neck flexion/extension		
		Extension	Neutral	Flexion
X (mm)	Eyes open	1.47 ± 1.77 ++	1.50 ± 1.82	1.67 ± 1.75
	Eyes closed	1.65 ± 1.77	1.48 ± 1.79	1.62 ± 1.76
Sx (mm)	Eyes open	6.06 ± 2.20 ++	6.23 ± 2.39	6.53 ± 2.37
	Eyes closed	10.4 ± 4.54 ** ++	9.35 ± 3.89	9.63 ± 3.86
Sr (mm)	Eyes open	3.03 ± 1.10 ++	3.10 ± 1.20	3.28 ± 1.25
	Eyes closed	5.21 ± 2.31 ** ++	4.65 ± 1.90	4.82 ± 1.91
Sl (mm)	Eyes open	3.04 ± 1.12 ++	3.12 ± 1.17	3.27 ± 1.25
	Eyes closed	5.20 ± 2.26 ** ++	4.71 ± 2.01	4.77 ± 1.93

** significantly (p<0.01) greater than neutral.
++ significantly (p<0.01) greater or less than flexion.

Table 4.7 The interaction between sex, vision and neck flexion/extension on the mediolateral centre of gravity projection (X) and the magnitude of mediolateral sway (Sx) (separately to the right (Sr) and left (Sl)) (mean ± SD).

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
Y (mm)	Left	1.61 ± 2.01	1.67 ± 2.01	1.64 ± 2.01
	Looking ahead	1.74 ± 2.07 **	2.08 ± 2.07	1.79 ± 2.07 **
	Right	1.68 ± 1.92	1.72 ± 1.92	1.69 ± 1.97
Sy (mm)	Left	6.86 ± 3.07	6.55 ± 2.69	6.87 ± 3.12
	Looking ahead	6.89 ± 3.14 ** ++	6.29 ± 2.93	6.37 ± 2.52
	Right	7.11 ± 3.26 ** ++	6.57 ± 2.82	6.63 ± 2.85
Sa (mm)	Left	3.42 ± 1.58	3.30 ± 1.36	3.41 ± 1.52
	Looking ahead	3.42 ± 1.52 ** ++	3.14 ± 1.44	3.14 ± 1.28
	Right	3.56 ± 1.61 ** ++	3.27 ± 1.42	3.29 ± 1.35
Sp (mm)	Left	3.44 ± 1.49	3.25 ± 1.35	3.46 ± 1.64
	Looking ahead	3.52 ± 1.72 ** ++	3.16 ± 1.51	3.18 ± 1.26
	Right	3.55 ± 1.67 ** ++	3.30 ± 1.41	3.29 ± 1.36
TLy (mm)	Left	57.3 ± 11.1	56.2 ± 10.5	57.5 ± 12.1 **
	Looking ahead	58.1 ± 12.16 ++	57.2 ± 11.0	56.3 ± 9.9
	Right	58.1 ± 11.64 ++	57.2 ± 11.7	56.3 ± 10.5
Vym (mm)	Left	2.86 ± 0.55	2.81 ± 0.52	2.88 ± 0.61 **
	Looking ahead	2.90 ± 0.61 ++	2.84 ± 0.60	2.82 ± 0.50
	Right	2.90 ± 0.58 ++	2.86 ± 0.59	2.81 ± 0.53

** significantly ($p<0.01$) greater or less than neutral.
++ significantly ($p<0.01$) greater than flexion.

Table 4.8 **The interaction between neck rotation and neck flexion/extension in the anteroposterior direction on the centre of gravity projection (Y), magnitude of anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), path length (TLy) and mean velocity of sway (Vym) (mean ± SD).**

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
Females Y (mm)	Left	1.91 ± 2.45 **	2.05 ± 2.43	1.97 ± 2.47
	Looking ahead	2.05 ± 2.58 **	2.34 ± 2.58	2.22 ± 2.54
	Right	1.97 ± 2.32	2.11 ± 2.26	1.97 ± 2.38
Males Y (mm)	Left	1.34 ± 1.45	1.32 ± 1.47	1.34 ± 1.42
	Looking ahead	1.46 ± 1.40 **	1.83 ± 1.42	1.40 ± 1.41 **
	Right	1.41 ± 1.42	1.36 ± 1.46	1.42 ± 1.46

** significantly ($p<0.01$) less than neutral.

Table 4.9 **The interaction between sex, neck rotation and neck flexion/extension on the anteroposterior centre of gravity projection (Y) (mean ± SD).**

Interaction between vision, neck rotation and neck flexion/extension

The analyses of variance revealed significant interactions between vision, neck rotation and neck flexion/extension for Sp, TL, TLy and Vm. As shown in Table 4.10 there was a significant ($p<0.01$) increase in Sp with visual feedback when the neck was rotated to the right or left and flexed compared with looking directly ahead. Without visual feedback Sp significantly ($p<0.01$) increased when looking directly ahead or when rotated to the right with extension compared with the neck in neutral or flexed. In addition, Sp significantly ($p<0.01$) increased when the neck was rotated to the left with extension or flexion compared with neutral.

For total path length (Table 4.10) no significant differences were observed when standing with eyes open for any combination of neck positions. However, without visual feedback there was a significant ($p<0.01$) increase in TL when looking directly ahead or with the neck rotated to the right with extension compared with flexion, as well as when the neck was rotated to the left with extension or flexion compared to neutral. This difference was due to an increase TLy.

For the mean velocity of sway (Table 4.10) no differences were observed with visual feedback with any combination of neck positions. However, without visual feedback there was a significant ($p<0.01$) increase in Vm when looking directly ahead or with the neck rotated to the right and extended compared with flexion, and when rotated to the left and extended or flexed compared to neutral. The difference was due to the correlation with TL.

Eyes open

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
Sp (mm)	Left	2.77 ± 0.99	2.71 ± 0.99	2.87 ± 0.96 **
	Looking ahead	2.61 ± 1.04	2.44 ± 0.95	2.58 ± 0.81
	Right	2.71 ± 0.99	2.57 ± 0.71	2.78 ± 0.82 **
TL (mm)	Left	85.5 ± 12.9	84.7 ± 13.4	85.6 ± 13.2
	Looking ahead	82.7 ± 11.8	83.3 ± 13.1	83.8 ± 12.9
	Right	85.4 ± 14.2	84.4 ± 12.5	84.6 ± 11.7
TLy (mm)	Left	53.8 ± 8.63	53.2 ± 8.51	54.2 ± 9.52
	Looking ahead	52.7 ± 7.48	53.4 ± 8.56	53.0 ± 8.08
	Right	54.0 ± 9.15	53.3 ± 8.17	53.3 ± 7.25
Vm (mm/s)	Left	2.69 ± 0.43	2.66 ± 0.43	2.71 ± 0.48
	Looking ahead	2.63 ± 0.37	2.64 ± 0.53	2.65 ± 0.40
	Right	2.70 ± 0.46	2.67 ± 0.41	2.66 ± 0.36

** significantly ($p<0.01$) greater than neutral.

Eyes closed

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
Sp (mm)	Left	4.10 ± 1.61 **	3.78 ± 1.46	4.05 ± 1.95 **
	Looking ahead	4.44 ± 1.78 ** ++	3.87 ± 1.63	3.79 ± 1.34
	Right	4.39 ± 1.79 ** ++	4.03 ± 1.55	3.80 ± 1.59
TL (mm)	Left	97.3 ± 18.7 **	94.5 ± 17.8	96.6 ± 19.5 **
	Looking ahead	101.0 ± 20.2 ++	97.6 ± 19.2	95.5 ± 17.4
	Right	98.9 ± 20.8 ++	97.6 ± 21.3	95.2 ± 19.4
TLy (mm)	Left	60.7 ± 12.2 **	59.2 ± 11.5	60.9 ± 13.5 **
	Looking ahead	63.4 ± 13.5 ++	61.0 ± 11.8	59.6 ± 10.6
	Right	62.1 ± 12.5 ++	61.1 ± 13.4	59.3 ± 12.3
Vm (mm/s)	Left	4.86 ± 0.94 **	4.73 ± 0.89	4.83 ± 0.98 **
	Looking ahead	5.05 ± 1.01 ++	4.88 ± 0.96	4.77 ± 0.87
	Right	4.95 ± 1.04 ++	4.88 ± 1.06	4.76 ± 0.97

** significantly ($p<0.01$) greater than neutral.
++ significantly ($p<0.01$) greater than flexion.

Table 4.10 **The interaction between vision, neck rotation and neck flexion/extension on the magnitude of sway in the posterior direction (Sp), total path length (TL), total anteroposterior path length (TLy) and mean velocity of sway (Vm) (mean ± SD).**

4.4 Discussion

Significant difference in height and foot length, and therefore eye level height, were observed between the female and male groups. Nevertheless, because of the close correlation between height and foot length there should be no disadvantage in postural control in smaller individuals with a smaller surface area of support. The differences in eye-object distance between subjects is unlikely to have had any influence on postural sway behaviour since each subject focused on a specific identified area within the visual field; moreover no account was taken of differences in visual acuity between subjects. The relative differences in eye-object distance between the sexes would not be expected to produce significant angular changes in either rotation or flexion/extension of the neck.

Differences were observed between the sexes with females having a greater total path length and mean velocity of sway than males. Similar to standing on a normal support surface (Horak and Nashner 1986), standing on the force platform in this experiment leads to subjects employing the ankle strategy to maintain balance. Because of the larger movements at the ankle joint and stronger gastrocnemius and tibialis anterior activation in smaller subjects (Berger et al. 1992) and the fact that lateral sway increases when standing with feet together (Kollegger et al. 1989), may be one explanation why the smaller female subjects show a greater path length and velocity of sway in the mediolateral direction than males. It is the observed increase in mediolateral path length and velocity of sway that leads to the increase in total path length and mean velocity of sway.

Although lower limb proprioceptive input is said to be sufficient for postural control (Fitzpatrick et al. 1994b) when standing with the feet together, this input by itself is not adequate to elicit an increase in mean sway velocity (Day et al. 1993). In this experiment visual feedback was observed to be a major influence on postural sway behaviour even though it did not affect the direction of sway. However, neck rotation either to the right or left appears to have this role in postural control. It is suggested that neck proprioceptor input is important when the neck muscles are working asymmetrically (i.e. when the muscles of one side shorten while those on the opposite side lengthen), since no such effect was observed in neck flexion/extension (i.e. when both sets of neck muscles are the same length). Vibration of the dorsal neck muscles has been observed to evoke forward body movement with deviation to the opposite side (Smetanin et al. 1993). As expected the direction of sway was not influenced by static stimulation of the vestibular system since during galvanic stimulation displacement of the centre of body mass is always close to the frontal plane (Mihalik 1992). In agreement with the study of Lund (1980) rotation of the neck either to the left or right also induced instability. It is, therefore, concluded that this instability is the result of neck proprioceptive input.

Flexion and extension of the neck appears to have a destabilising effect on posture, with extension having a greater influence than flexion. It has previously been shown that head-neck extension increases body sway due to vestibular sensory deficiency (Jackson and Epstein 1991) and compression of the vertebral arteries (Brandt et al. 1981). However, it is equally possible that the changes observed here are due to resetting of the internal gain as a result of head position. Neck extension has a more powerful effect because it is interpreted centrally as if the body is falling backward, with neck extension leading to vestibular depolarisation (Livingston 1990; Sherwood 1997). Stimulation of the vestibular system is known to modify activity in the lower limb muscles (Tokita et al. 1981), which have an important role in postural control. However, the powerful effects of the vestibular system are dependent on whether vestibular cues are required for postural stability (Fitzpatrick et al. 1994a). The effect of neck flexion/extension in this experiment is thought to be due to the influence of the vestibular system rather than the neck proprioceptive input, since bilateral vibration of the dorsal neck muscles induces whole body forward sway (Smetanin et al. 1993). The COG projection in the anteroposterior direction should therefore move anteriorly and not posteriorly as observed in this experiment.

There appears to be an interaction between vision and neck rotation in the control of postural sway behaviour. Without visual feedback neck rotation does not increase instability, however with visual feedback it leads to postural destabilisation. In addition, it is known that vibration to one side of the dorsal neck muscles induces a visual illusion of target movement (Biguer et al. 1988; Roll et al. 1991; Smetanin et al. 1993). It is suggested, therefore that neck proprioceptive input during neck rotation is not directly linked with visual feedback, but may induce visual feedback destabilisation, therefore causing postural instability. It is possible that the interaction of vision and neck proprioception depends on the specific influence of the neck input on the visual system.

The interaction between vision and neck flexion/extension appears to influence postural sway behaviour. Vision appears to counteract the instability created by neck extension, such that with visual feedback neck extension does not induce instability. It is further suggested, from the observation of Zacharias and Young (1981), that vision and the vestibular system are directly linked to each other, with the agreement depending on vision rather than the vestibular input associated with neck extension. The vestibular input from neck flexion appears to mismatch with visual feedback, perhaps due to the hyperpolarisation of the vestibular input (Livingston 1990; Sherwood 1997). The interaction between visual and vestibular cues seems to have a greater effect in males than in females. Hence, it is possible that vision is a more important factor in postural stability in males than it is in females supporting the observations of Kollegger et al. (1992).

There appears to be an important interaction between neck rotation and neck flexion/extension in postural sway behaviour, particularly in the anteroposterior direction: the influence of neck flexion/extension being more dominant than neck rotation. The vestibular system has been observed to influence the lower limb muscles (Tokita et al. 1981), such that when standing with the feet together anteroposterior balance is totally under ankle control (Winter et al. 1996). It is, therefore suggested that the linearly integrated input between vestibular and neck proprioception (Anastasopoulos and Mergner 1982; Karnath et al. 1994) depends on vestibular input. The interaction between vestibular and neck proprioceptive system seems to have greater effect in females than in males.

Without visual feedback the interaction between neck flexion/extension and neck rotation results in an increase in postural sway, but with visual feedback this combination does not lead to increase instability. There is an interaction between the visual, vestibular and neck proprioception systems, with vision providing a stabilising factor compensating for the instability created by the interaction of vestibular and neck proprioception input.

4.5 Summary

Static visual, vestibular and neck proprioception all influence postural maintenance, with visual input being the most important but with neck proprioception playing an important role in controlling sway direction. The interaction between vision and neck proprioception, vision and vestibular input associated with neck flexion and vestibular input and neck proprioception, leads to destabilisation of posture and an increase in postural sway behaviour. Nevertheless, the interaction between vision, vestibular and neck proprioception is important for postural maintenance.

Chapter 5

Experiment 2: Responses to dynamic vestibular and neck proprioceptor stimulation while visually tracking a moving target

5.1 Introduction

During normal standing the vestibular system does not modulate lower limb muscle activity to assist postural stabilisation (Fitzpatrick et al. 1994b). However, the vestibular system has been reported to be necessary for postural maintenance when the body is under conditions of instability (Martin 1965), as well as playing a role during fast postural movement (Inglis et al. 1995).

The role of the neck proprioceptor input on postural control has been investigated by Lund (1980) and Smetanin et al. (1993), who both observed an increase in body displacement with vibration of the dorsal neck muscles.

Since postural destabilisation can result from object motion (Dichgans et al. 1972; Bronstein 1986; Yardley et al. 1992) and neck proprioceptive input (Lund 1980), with the vestibular system helping to control instability (Martin 1965), it is possible that there may be an interaction between vestibular and neck proprioceptor inputs in postural control. Mergner et al. (1991) have previously shown an interaction between vestibular and neck proprioceptor inputs in the perception of trunk motion in space. The aim of the present study, therefore is to investigate the influence of dynamic vestibular and neck proprioception stimulation on the control of postural sway behaviour.

5.2 Materials and methods

Thirty healthy subjects (15 females, 15 males), aged between 18 and 43 years, agreed to participate in this experiment.

Eight combinations of head-neck posture were employed in tracking a moving target, each at two velocities of head movement (0.2m/s and 1.0m/s). For tracking in the frontal plane the neck was either in neutral (N), extended (E) or flexed (F) 45^0, while for tracking vertically the subject was looking directly ahead (A) or the neck was rotated 45^0 to the right (R) or left (L). The remaining conditions had the subject tracking obliquely from the neck extended and rotated to the right to flexed and rotated to the left (RE) or from the neck extended and rotated to the left to flexed and rotated to the right (LE). Postural sway behaviour was recorded with the subject standing comfortably erect with feet together, wearing vision-restricting goggles and tracking the moving object by moving the head (for further details see Chapter 3 part 3.7.2).

Three-way analyses of variance were conducted for each sway parameter (Chapter 3 part 3.3) with sex, velocity of head movement and direction of head movement as independent variables in order to determine the influence of each on postural sway behaviour. t-tests were further conducted where appropriate to determine differences in each independent variable. t-tests were also conducted on the subject characteristics. Unless otherwise stated all differences are at the 5% level of significance.

5.3 Results

5.3.1 Subject characteristics

The characteristics of the population studied are given in Table 5.1, with the data being presented for the whole group as well as for females and males separately. There was no difference in age between females and males, however height, foot length and eye level height were all significantly ($p<0.01$) greater and eye-object distance significantly ($p<0.01$) smaller in males.

Subject characteristics	All	Females	Males
Age (year)	24.1 ± 5.38	25.4 ± 6.29	22.9. ± 4.12
Height (cm)	168.3 ± 10.6	160.9 ± 8.76	175.7 ± 6.04 **
Foot length (cm)	24.4 ± 1.80	23.3 ± 1.08	25.4 ± 1.74 **
Eye-Object distance (cm)	49.2 ± 1.80	50.2± 1.08	48.1 ± 1.74 **
Eye level height (cm)	157.6 ± 10.2	150.6 ± 8.80	164.5 ± 5.71 **

** significantly ($p<0.01$) greater or less than female value.

Table 5.1 The characteristics the subjects (15 females and 15 males) who participated in Experiment 2 (mean ± SD).

5.3.2 Analyses of variance

The results of the various analyses of variance are presented in Appendix 6, showing sex, velocity of head movement and direction of head movement, as well as their interactions on the various parameters of postural sway behaviour.

Sex

Few differences in sway behaviour were observed between females and males, the differences being restricted to the coordinates of the COG projection. In females the COG projection was significantly more to the right ($p<0.01$) (female 4.34 ± 2.13; male 1.78 ± 1.65) and anterior ($p<0.05$) (female 1.30 ± 2.25; male -0.46 ± 1.81) than in males.

Velocity of head movement

The velocity of head movement influenced all sway parameters except the COG projection and the angle of sway from the sagittal plane. As shown in Table 5.2 the higher velocity resulted in a significant ($p<0.01$) increase in the magnitude of mediolateral sway (Sx), as well as separately to the right (Sr) and left (Sl), and of anteroposterior sway (Sy) and separately anteriorly (Sa) and posteriorly (Sp). Similarly, head movement at the higher velocity significantly ($p<0.01$) increased the total path length (TL), and the mediolateral (TLx) and anteroposterior (TLy) path lengths separately. A similar pattern was observed for the mean velocity of sway (Vm), and for the mean mediolateral (Vxm) and anteroposterior (Vym) velocities separately.

Postural sway parameter	**Velocity of head movement**	
	0.2 m/s	**1.0 m/s**
X (mm)	3.06 ± 2.28	3.05 ± 2.32
Y (mm)	0.42 ± 2.25	0.42 ± 2.19
Sx (mm)	2.06 ± 0.89	2.67 ± 1.33 **
Sr (mm)	1.03 ± 0.46	1.34 ± 0.69 **
Sl (mm)	1.03 ± 0.46	1.33 ± 0.67 **
Sy (mm)	1.60 ± 0.64	2.22 ± 0.91 **
Sa (mm)	0.81 ± 0.34	1.12 ± 0.51 **
Sp (mm)	0.79 ± 0.32	1.10 ± 0.46 **
TL (mm)	130.5 ± 50.9	167.9 ± 74.8 **
TLx (mm)	84.9 ± 36.8	110.6 ± 57.9 **
TLy (mm)	79.1 ± 29.5	100.8 ± 39.6 **
Vm (mm/s)	6.55 ± 2.55	8.42 ± 3.75 **
Vxm (mm/s)	4.26 ± 1.85	5.55 ± 2.91 **
Vym (mm/s)	3.97 ± 1.48	5.06 ± 1.99 **
Ay (°)	14.3 ± 37.8	13.7 ± 33.0

** significantly (p<0.01) greater than lower velocity.

Table 5.2 **The influence of the velocity of head movement on the centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions, magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), total path length (TL), mediolateral (TLx) and anteroposterior (TLy) path lengths, mean velocity of sway (Vm), mediolateral (Vxm) and anteroposterior (Vym) sway velocities, and angle of sway from the sagittal plane (Ay) (mean ± SD).**

Interaction between sex and the velocity of head movement

The analyses of variance showed an interaction between sex and the velocity of head movement for Y only. At both velocities females showed a significant (p<0.01) anterior shift of the COG compared with males: lower velocity 1.34 ± 2.25 mm and –0.51 ± 1.84 mm, and higher velocity 1.26 ± 2.26 mm and –0.42 ± 1.78 mm respectively.

Direction of head movement

The direction of head movement significantly influenced most postural sway parameters. There was no significant difference in the mean mediolateral COG position with either vertical, horizontal or oblique head movements. There was however a significant shift in the mean anteroposterior COG projection, except with the neck flexed, when moving horizontally (Table 5.3). No differences were observed in head movement diagonally compared with horizontal or vertical head movement.

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
Y (mm)	0.52 ± 2.29 **	0.71 ± 2.43 **	0.22 ± 2.25

* significantly (p<0.01) greater than flexion.

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
Y (mm)	0.31 ± 2.12	0.36 ± 2.20	0.28 ± 2.20

Postural Sway Parameter	Diagonal head movement	
	LE	RE
Y (mm)	0.46 ± 2.23	0.50 ± 2.11

Table 5.3 The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the anteroposterior centre of gravity projection (Y) (mean ± SD).

As shown in Table 5.4 there was a significant increase in Sx, Sr and Sl with horizontal head movement with the neck extended (p<0.01) or in neutral compared with neck flexed. Movement in the vertical direction also showed significant increases in Sx, Sr and Sl when movement was with the neck rotated to either the right or left compared with looking directly ahead. There was no difference for diagonal head movement. There was, however a significant (p<0.01) decrease in Sx, Sr and Sl with diagonal head movement compared with horizontal head movement with the neck extended.

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
Sx (mm)	2.76 ± 1.46 **	2.55 ± 1.36 *	2.17 ± 1.03
Sr (mm)	1.39 ± 0.75 **	1.29 ± 0.71 *	1.09 ± 0.52
Sl (mm)	1.37 ± 0.74 **	1.26 ± 0.67 *	1.09 ± 0.53

* p<0.05, ** p<0.01 significantly greater than flexion.

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
Sx (mm)	2.42 ± 1.18 *	2.12 ± 0.88	2.45 ± 1.10 *
Sr (mm)	1.21 ± 0.61 *	1.06 ± 0.43	1.22 ± 0.57 *
Sl (mm)	1.20 ± 0.59 *	1.07 ± 0.46	1.23 ± 0.59 *

* significantly (p<0.05) greater than looking directly ahead.

Postural sway parameter	Diagonal head movement	
	LE	RE
Sx (mm)	2.27 ± 1.12 **	2.21 ± 1.07 **
Sr (mm)	1.13 ± 0.57 **	1.11 ± 0.55 **
Sl (mm)	1.13 ± 0.57 **	1.10 ± 0.54 **

** significantly (p<0.01) less than horizontal head movement with extension.

Table 5.4 **The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of mediolateral sway (Sx) (separately to the right (Sr) and left (Sl)) (mean ± SD).**

The influence of the direction of head movement on the mean magnitude of anteroposterior sway is shown in Table 5.5. For horizontal head movement there was a significant increase in Sy in extension (p<0.01) or neutral compared with flexion. This increase was due to the observed increase in Sa rather than Sp. For vertical head movement there was no difference for Sy or Sa, however, there was a significant decrease in Sp with the neck rotated to either the right (p<0.01) or left compared with looking directly ahead. There was no difference in Sy, Sa and Sp for diagonal head movement.

There was significant (p<0.01) increase in Sy, Sa and Sp with diagonal head movement compared with horizontal head movement with the neck flexed. There also was significant decrease in Sy, due to the decrease in Sp, with diagonal head movement compared with vertical head movement with rotation to the left.

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
Sy (mm)	1.99 ± 0.97 **	1.81 ± 1.00 *	1.59 ± 0.73
Sa (mm)	0.97 ± 0.50 **	0.91 ± 0.54 *	0.81 ± 0.37
Sp (mm)	1.02 ± 0.49	0.89 ± 0.47	0.78 ± 0.37

* p<0.05, ** p<0.01 significantly greater than flexion.

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
Sy (mm)	2.01 ± 0.73	2.20 ± 0.90	2.02 ± 0.83
Sa (mm)	1.01 ± 0.41	1.09 ± 0.46	1.06 ± 0.56
Sp (mm)	0.99 ± 0.40 *	1.11 ± 0.46	0.95 ± 0.42 **

* p<0.05, ** p<0.01 significantly less than looking directly ahead.

Postural sway parameter	Diagonal head movement	
	LE	RE
Sy (mm)	1.82 ± 0.66 * +	1.86 ± 0.75 * +
Sa (mm)	0.93 ± 0.35 *	0.95 ± 0.39 *
Sp (mm)	0.89 ± 0.34 * +	0.90 ± 0.38 * ++

* significantly (p<0.01) greater than horizontal head movement with flexion.
+ p<0.05, ++ p<0.01 significantly less than vertical head movement with rotation to the left.

Table 5.5 **The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)) (mean ± SD).**

The direction of head movement also had an effect on the path length of sway (Table 5.6). For horizontal head movement with the neck extended or in neutral TL, TLx and TLy was significantly (p<0.01) increased when compared with neck flexion. For vertical head movement only TLx showed a difference, being greater with rotation to the right or left compared with looking directly ahead. No differences were observed for diagonal head movement. There was significant (p<0.01) decrease in TL, TLx and TLy with diagonal head movement compared with horizontal head movement with the neck extended. Only TLy showed a significant decrease for diagonal head movement compared with vertical head movement with rotation either to the right or left.

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
TL (mm)	170.6 ± 80.5 **	158.8 ± 84.8 **	139.0 ± 68.4
TLx (mm)	113.7 ± 59.0 **	108.5 ± 63.1 **	93.7 ± 53.6
TLy (mm)	101.1 ± 45.7 **	91.3 ± 45.9 **	80.7 ± 34.0

** significantly ($p<0.01$) greater than flexion.

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
TL (mm)	149.2 ± 61.3	144.5 ± 53.3	150.3 ± 59.4
TLx (mm)	96.2 ± 46.9 **	87.9 ± 37.6	97.8 ± 45.1 **
TLy (mm)	91.8 ± 33.0	93.8 ± 33.6	91.4 ± 32.1

** significantly ($p<0.01$) greater than looking directly ahead.

Postural sway parameter	Diagonal head movement	
	LE	RE
TL (mm)	141.3 ± 61.4 *	140.0 ± 53.9 *
TLx (mm)	93.7 ± 46.8 *	90.6 ± 41.0 *
TLy (mm)	84.1 ± 32.6 * +	85.5 ± 29.8 * ++

** significantly ($p<0.01$) less than horizontal head movement with extension.

+ $p<0.05$, ++ $p<0.01$ significantly less than vertical head movement with rotation to the rigth or left.

Table 5.6 The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the total path length (TL) and path length in the mediolateral (TLx) and anteroposterior (TLy) directions (mean ± SD).

As shown in Table 5.7 a similar pattern for horizontal, vertical and diagonal head movement, as well as diagonal head movement compared with horizontal and vertical head movement, was observed for the mean velocity of sway and the mean mediolateral and anteroposterior velocities separately as was observed for path length.

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
Vm (mm/s)	8.56 ± 4.04 **	7.97 ± 4.26 **	6.97 ± 3.43
Vxm (mm/s)	5.71 ± 2.96 **	5.45 ± 3.17 **	4.70 ± 2.69
Vym (mm/s)	5.07 ± 2.29 **	4.58 ± 2.31 **	4.05 ± 1.71

** significantly (p<0.01) greater than flexion.

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
Vm (mm/s)	7.49 ± 3.07	7.25 ± 2.67	7.54 ± 2.98
Vxm (mm/s)	4.83 ± 2.35 **	4.41 ± 1.89	4.91 ± 2.26 **
Vym (mm/s)	4.61 ± 1.66	4.71 ± 1.69	4.58 ± 1.61

** significantly (p<0.01) greater than looking directly ahead.

Postural sway parameter	Diagonal head movement	
	LE	RE
Vm (mm/s)	7.09 ± 3.08 *	7.03 ± 2.70 *
Vxm (mm/s)	4.70 ± 2.34 *	4.55 ± 2.06 *
Vym (mm/s)	4.22 ± 1.63 * +	4.29 ± 1.50 * ++

** significantly (p<0.01) less than horizontal head movement with extension.

+ p<0.05, ++ p<0.01 significantly less than vertical head movement with rotation to the rigth or left.

Table 5.7 The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the mean velocity of sway (Vm) and mean sway velocity in the mediolateral (Vxm) and anteroposterior (Vym) directions (mean ± SD).

Interaction between the velocity and direction of head movement

The analyses of variance showed a significant interaction between the velocity and direction of head movement, but only for those parameters associated with sway in the anteroposterior direction, except the COG projection. As shown in Table 5.8 at the low velocity of head movement (0.2m/s) there were significant (p<0.01) increases in Sy, Sa and Sp for horizontal head movement with the neck extended compared with neutral or flexion. For vertical or diagonal head movement (Table 5.8) at the low velocity no differences were observed in Sy, Sa or Sp. However, at the high velocity (1.0m/s) there were significant increases in Sy, Sa and Sp for horizontal movement with the neck in neutral and extended (p<0.01) when compared with flexion. There was also a significant (p<0.01) decrease in Sy for vertical head movement with rotation to the right and left compared with looking directly ahead. The decrease in Sy was the result of the decrease in Sp rather than Sa. There was no difference for diagonal movement at the higher velocity.

Postural sway parameter	Velocity of head movement	Horizontal head movement		
		Extension	Neutral	Flexion
Sy (mm)	0.2 m/s	1.81 ± 0.83 **	1.46 ± 0.57	1.46 ± 0.59
	1.0 m/s	2.17 ± 1.08 ++	2.16 ± 1.21 +	1.72 ± 0.83
Sa (mm)	0.2 m/s	0.89 ± 0.43 **	0.73 ± 0.30	0.76 ± 0.34
	1.0 m/s	1.05 ± 0.56 ++	1.10 ± 0.66 +	0.85 ± 0.40
Sp (mm)	0.2 m/s	0.92 ± 0.43 **	0.72 ± 0.28	0.70 ± 0.26
	1.0 m/s	1.12 ± 0.54 ++	1.06 ± 0.56 +	0.86 ± 0.44

** significantly ($p<0.01$) greater than neutral and flexion.
+ $p<0.05$, ++ $p<0.01$ significantly greater than flexion.

Postural sway parameter	Velocity of head movement	Vertical head movement		
		Left	Looking ahead	Right
Sy (mm)	0.2 m/s	1.66 ± 0.62	1.65 ± 0.55	1.72 ± 0.75
	1.0 m/s	2.35 ± 0.68 **	2.75 ± 0.85	2.31 ± 0.81 **
Sa (mm)	0.2 m/s	0.85 ± 0.36	0.83 ± 0.31	0.88 ± 0.36
	1.0 m/s	1.18 ± 0.40	1.35 ± 0.44	1.25 ± 0.67
Sp (mm)	0.2 m/s	0.81 ± 0.31	0.82 ± 0.26	0.84 ± 0.41
	1.0 m/s	1.18 ± 0.40 **	1.39 ± 0.45	1.07 ± 0.42 **

** significantly ($p<0.01$) less than looking direction ahead.

Postural sway parameter	Velocity of head movement	Diagonal head movement	
		LE	RE
Sy (mm)	0.2 m/s	1.56 ± 0.59	1.47 ± 0.51
	1.0 m/s	2.08 ± 0.64	2.08 ± 0.64
Sa (mm)	0.2 m/s	0.80 ± 0.33	0.74 ± 0.27
	1.0 m/s	1.06 ± 0.32	1.06 ± 0.32
Sp (mm)	0.2 m/s	0.76 ± 0.31	0.73 ± 0.25
	1.0 m/s	1.02 ± 0.32	1.02 ± 0.32

Table 5.8 **The interaction between velocity of head movement and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of anteroposterior sway (Sy), (separately anteriorly (Sa) and posteriorly (Sp)) (mean ± SD).**

When diagonal head movement was compared with horizontal movement at 0.2m/s there was a significant decrease in Sy, due to the significant ($p<0.01$) decrease in Sp, LE compared with neck extension. There was also a significant ($p<0.01$) decrease in Sy, due to the significant ($p<0.01$) decrease in Sa and Sp, for RE compared with neck extension. At 1.0m/s there was significant ($p<0.01$) increase in Sy, Sa and Sp with both diagonal head movements compared with horizontal head movement with flexion. There were no differences between diagonal and vertical head movement.

As shown in Table 5.9 at the low velocity of horizontal head movement TLy was significantly ($p<0.01$) increased in extension compared with neutral or flexion. At the higher velocity of horizontal head movement in neutral or extension ($p<0.01$) TLy significantly increased compared with flexion. There were no differences in TLy for vertical or diagonal head movements at either velocity.

At the lower velocity there was significant ($p<0.01$) decrease in TLy for both diagonal head movements compared with horizontal head movement with extension and vertical head movement with rotation to the right. At the higher velocity a significant decrease in TLy was observed for both diagonal head movements compared with horizontal head movement with extension, but a significant ($p<0.01$) increase with flexion. Only LE diagonal head movement resulted in a significant ($p<0.01$) decrease in TLy compared with vertical head movement with rotation to the left. A similar pattern was observed for Vym (Table 5.9).

Postural sway parameter	Velocity of head movement	Horizontal head movement		
		E	N	F
TLy (mm)	0.2 m/s	92.2 ± 41.5 **	76.2 ± 24.6	76.4 ± 29.0
	1.0 m/s	110.0 ± 48.7 ++	106.3 ± 56.8 +	85.1 ± 38.4
Vym (mm/s)	0.2 m/s	4.62 ± 2.08 **	3.83 ± 1.23	3.83 ± 1.45
	1.0 m/s	5.52 ± 2.44 ++	5.33 ± 2.85 +	4.27 ± 1.93

** significantly ($p<0.01$) greater than neutral and flexion.
\+ $p<0.05$, ++ $p<0.01$ significantly greater than flexion.

Postural sway parameter	Velocity of head movement	Vertical head movement		
		L	A	R
TLy (mm)	0.2 m/s	79.3 ± 28.5	77.1 ± 22.2	82.2 ± 30.5
	1.0 m/s	104.3 ± 32.9	110.5 ± 35.0	100.5 ± 31.5
Vym (mm/s)	0.2 m/s	3.98 ± 1.43	3.87 ± 1.11	4.12 ± 1.53
	1.0 m/s	5.23 ± 1.65	5.54 ± 1.76	5.04 ± 1.58

Postural sway parameter	Velocity of head movement	Diagonal head movement	
		LE	RE
TLy (mm)	0.2 m/s	75.1 ± 28.8	74.1 ± 26.7
	1.0 m/s	93.1 ± 34.1	96.8 ± 28.8
Vym (mm/s)	0.2 m/s	3.77 ± 1.45	3.72 ± 1.34
	1.0 m/s	4.67 ± 1.71	4.86 ± 1.44

Table 5.9 The interaction between velocity of head movement and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the path length and mean sway velocity in the anteroposterior (TLy and Vym) direction (mean ± SD).

5.4 Discussion

Although the age range of the subject in this experiment is greater than that of Experiment 1 (Chapter 4), there is no difference in age between the female and male groups. However, as in Experiment 1 height, foot-length and therefore eye level height are greater and eye-object distance is smaller in males.

The influence of sex on postural sway behaviour in this experiment can be seen in the COG projection in both the mediolateral and anteroposterior directions, showing greater changes in females than in males. The difference is most probably due to visual feedback rather than feedback from the vestibular or neck proprioceptive systems since object motion induces body sway (Dichgans et al. 1972; Bronstein 1986). Males showed more consistency in the COG projection in the mediolateral direction than did females. Static visual feedback has been shown to be a more important stabilising factor in males than females (Kollegger et al. 1992). When tracking a moving object vision still appears to have more influence in males than females. It is, therefore suggested that vision has a stronger effect on the mediolateral COG projection in males than females, whereas it has more of a stabilising effect in the anteroposterior direction in females than males.

The velocity of head movement has a major influence on the magnitude, path length and velocity of sway in both the mediolateral and anteroposterior directions, all being increased at the higher velocity. Although vestibular stimulation is mainly generated during whole body rotation (Mergner et al. 1991, Kolev et al. 1996), head movement can also stimulate the vestibular system (Carpenter 1990; Livingston 1990; Pansky et al. 1992). In addition, the responses of vestibulospinal neurones depend on the direction of head, trunk and limb movement, as well as the frequency of stimulation (Perlmutter et al. 1999). Stimulation of the vestibular system causes an increase in postural sway (Johannson and Magnusson 1991; Magnusson et al. 1991; Fitzpatrick et al. 1994a; Inglis et al. 1995). In the present experiment the higher velocity of head movement led to increased postural instability, probably due to the greater stimulation of the vestibular system than occurs at the lower velocity does.

The interaction between sex and the velocity of head movement in controlling the COG projection in the anteroposterior direction shows that vestibular input seems to assist postural control in females more than it does in males. This may be due to the compensation of vestibular, as well as visual, input in females in controlling sway particularly in the anteroposterior direction.

Moving the head in various directions with difference neck positions has influences in both the mediolateral and anteroposterior directions. For horizontal head movement although neck flexion causes the COG projection to shift posteriorly, it also decreases mediolateral and anteroposterior sway magnitude, the total path length and velocity of sway. Movement of the COG projection posteriorly may be a compensation between forward head and backward trunk movement. It is suggested that vestibular input from neck flexion stabilises posture; on the other hand vestibular input from neck extension leads to postural instability. This differential effect of the vestibular system is possible due to different orientations of the vestibular labyrinths with neck flexion/extension. Vertical head movement with the neck rotated either to the right or left causes mediolateral postural destabilisation and also reduces the magnitude of posterior sway. It is suggested that neck proprioceptive input decreases postural stability in the mediolateral direction but increases it in the anteroposterior direction. Comparing horizontal or vertical head movement with diagonal head movement reveals an interaction between vestibular and neck proprioceptive inputs. During diagonal head movement there is the stabilising effect of neck extension on the vestibular system in the mediolateral direction. It appears that vestibular input decreases the destabilising effect of neck proprioceptive input on postural control in the mediolateral direction. For the magnitude of anteroposterior sway the interaction between vestibular and neck proprioceptive inputs is greater than the effect of neck flexion, but less than that of neck rotation. The effect of the vestibular-neck proprioceptive interaction on the magnitude of anteroposterior sway depends on both vestibular and neck proprioceptive input. In the regulation of path length and the mean velocity of sway, as well as for the anteroposterior path length and velocity of sway, the interaction between vestibular and neck proprioceptive inputs is dominated by the vestibular system.

The interaction between the velocity and direction of head movement appears to control postural behaviour in the anteroposterior direction, with the findings revealing the influence of the vestibular system in the anteroposterior direction. The vestibular input control depends on the velocity of head movement as seen with horizontal head movement. Furthermore, the vestibular system appears to assist neck proprioception in stabilising posture since there is a reduction in the magnitude of sway at the higher velocity during vertical head movement. In the interaction between the vestibular and neck proprioceptive systems the vestibular input is the important cue in controlling posture, since at the higher velocity of head movement the interaction results in increased sway behaviour than does vestibular input associated with neck flexion.

5.5 Summary

In dynamic situations individual vestibular and neck proprioceptive inputs, as well as the interaction between them, influence postural maintenance, with vestibular stimulation depending on the velocity of head movement. The vestibular input associated with neck extension destabilises posture, whereas that from neck flexion promotes stability. Neck proprioceptive input destabilises posture in the mediolateral direction but stabilises it in the anteroposterior direction. The interaction between vestibular and neck proprioceptive system stabilises posture in the mediolateral direction and depends on the vestibular input. Such interaction also influences sway in the anteroposterior direction, with vestibular input appearing to be the most important input.

Chapter 6

Responses to static and dynamic vestibular and neck proprioceptor stimulation

6.1 Introduction

The position of the head in space as well as head motion associated with postural maintenance is perceived by the vestibular (Carpenter 1990; Norre′ 1990) and neck proprioceptive (Abrahams 1977; Smetanin et al. 1993; Karnath et al. 1994) systems. Following from the results presented in Chapter 4 for the static stimulation and Chapter 5 for the dynamic stimulation, the question that arises is whether the response to static and dynamic stimulation of the vestibular and neck proprioceptive system on postural control is the same. The aim in this chapter therefore is to examine the influence of static and dynamic stimulation of the vestibular system, as well as neck proprioception, on postural sway behaviour.

6.2 Materials and methods

The data from sixteen subjects (9 females, 7 males) who participated in both Experiments 1 (Chapter 4) and 2 (Chapter 5) were compared and analysed.

The data from Experiments 1 (Chapter 4) and 2 (Chapter 5) were compared as follow (Figure 6.1a-c).

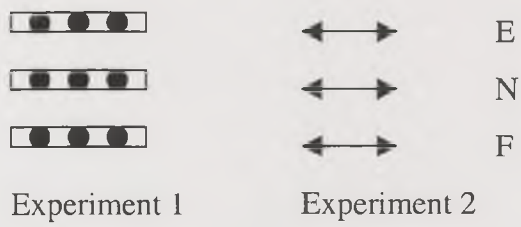
A. For horizontal head movement (Figure 6.1a) the data from the three static horizontal markers of Experiment 1 (Chapter 4) were summed to equate to neck extension (E), flexion (F) and neutral (N) to correspond to the dynamic condition of horizontal head movement with the neck extened (E), flexed (F) and neutral (N) for Experiment 2 (Chapter 5).

B. For vertical head movement (Figure 6.1b) the data from the three vertical markers of Experiment 1 (Chapter 4) were summed to equate to static looking directly ahead (A) or rotation either to the right (R) or left (L) to correspond to the dynamic condition of vertical head movement while looking directly ahead (A) or rotation either to the right (R) or left (L) for Experiment 2 (Chapter 5).

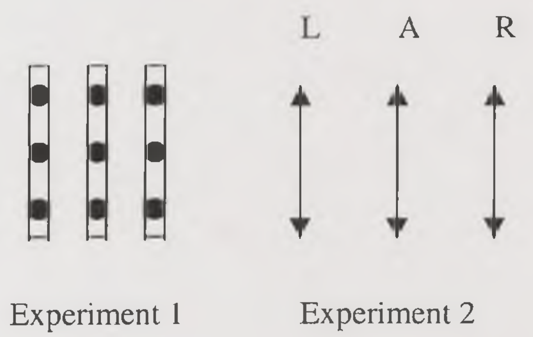
C. For diagonal head movement (Figure 6.1c) the data from the three diagonal markers of Experiment 1 (Chapter 4) were summed to equate to neck extension and rotation to the left to flexion and rotation to the right (LE) and neck extension and rotation to the right to flexion and rotation to the left (RE) in the static head condition to correspond to the dynamic condition of diagonal head movement with neck rotation to the left and extension to rotation to the right and flexion (LE) and neck rotation to the right and extension to rotation to the left and flexion (RE) for Experiment 2 (Chapter 5).

Three-way analyses of variance were conducted for each of the calculated sway parameters (Chapter 3 part 3.3) with sex, the velocity and direction of head movement as independent variables in order to determine the influence of each on postural sway behaviour. t-tests were conducted as appropriate to determine the significant differences in each group of independent variables. In addition, t-tests were conducted for subject characteristics. Unless otherwise stated all differences are at the 5% level of significance.

a. Horizontal head movement



b. Vertical head movement



c. Diagonal head movement

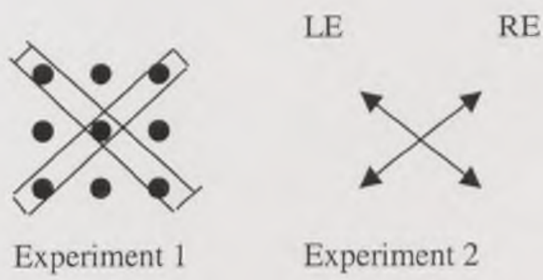


Figure 6.1 **The summation of 3 markers from Experiment 1 (Chapter 4) respectively to dynamic head movement in Experiment 2 (Chapter 5) (a) horizontally with 45^0 neck extension (E), 45^0 neck flexion (F) or neutral (N), (b) vertically with 45^0 neck rotation either to the right (R) or left (L) or looking ahead (A), (c) diagonally with neck rotation to the right and extended moving to the left and flexed (RE) or neck rotation to the left and extended moving to the right and flexed (LE).**

6.3 Results

6.3.1 Subject characteristics

The characteristics of the population studied are given in Table 6.1, with the data being presented for the whole group as well as for the female and male groups separately. There was no difference in age between females and males, however height, foot length and eye level height were significantly ($p<0.01$) greater and eye-object distance significantly ($p<0.01$) smaller in males than females.

Subject characteristics	All	Females	Males
Age (year)	23.4 ± 4.00	24.2 ± 4.36	22.3. ± 2.98
Height (cm)	165.1 ± 10.6	158.7 ± 9.01	173.4 ± 5.59 **
Foot length (cm)	24.6 ± 1.99	23.3 ± 0.83	26.1 ± 1.95 **
Eye-Object distance (cm)	48.9 ± 1.99	50.2± 0.83	47.4 ± 1.95 **
Eye level height (cm)	156.1 ± 10.5	159.6 ± 8.77	164.5 ± 5.16 **

** significantly ($p<0.01$) greater or less from female value.

Table 6.1 The characteristics of the subjects (9 females, 7 males) who participated in Experiments 1 and 2 (mean ± SD).

6.3.2 Analyses of variance

The results of the various analyses of variance are presented in Appendix 7, showing the influence of sex, the velocity (static/dynamic head condition) and the directions of head movement and their interactions on the various parameters of postural sway behaviour.

Sex

Few differences in sway behaviour were observed between females and males, the difference being restricted to the mediolateral COG. The projection was significantly further to the right in females (3.70 ± 2.19) than males (1.86 ± 1.75).

Static/dynamic head condition

Whether the head was static or moving had a significant influence on most sway parameters (Table 6.2). There was a significant ($p<0.01$) deviation to the right of the mediolateral COG projection with head movement at either 0.2m/s or 1.0m/s compared with the static condition. No difference was observed in the mediolateral COG projection between the two velocities of head movement. There was no difference in the anteroposterior COG projection or the angle of sway from the sagittal plane for any head condition.

Postural sway parameter	Head condition		
	Static	Dynamic	
		0.2m/s	1.0m/s
X (cm)	2.10 ± 2.09	3.28 ± 2.13 **	3.31 ± 2.19 **
Y (cm)	2.14 ± 2.55	0.37 ± 2.32	0.40 ± 2.30
Sx (cm)	0.67 ± 0.20	1.92 ± 0.74 **	2.51 ± 1.15 ++
Sr (cm)	0.33 ± 0.09	0.97 ± 0.41 **	1.27 ± 0.58 ++
Sl (cm)	0.34 ± 0.10	0.94 ± 0.36 **	1.25 ± 0.59 ++
Sy (cm)	0.55 ± 0.17	1.50 ± 0.49 **	2.15 ± 0.76 ++
Sa (cm)	0.28 ± 0.09	0.77 ± 0.27 **	1.09 ± 0.40 ++
Sp (cm)	0.27 ± 0.09	0.74 ± 0.25 **	1.06 ± 0.39 ++
TL (mm)	84.3 ± 13.8	121.2 ± 37.0 **	154.3 ± 54.6 ++
TLx (mm)	51.6 ± 8.68	77.9 ± 26.9 **	100.3 ± 41.7 ++
TLy (mm)	53.4 ± 9.00	74.2 ± 22.2 **	93.9 ± 30.3 ++
Vm (mm/s)	4.16 ± 0.71	6.08 ± 1.86 **	7.74 ± 2.74 ++
Vxm (mm/s)	2.58 ± 0.44	3.91 ± 1.35 **	5.03 ± 2.09 ++
Vym (mm/s)	2.65 ± 0.49	3.72 ± 1.11 **	4.71 ± 1.52 ++
Ay (^{o})	32.0 ± 34.6	14.0 ± 39.7	11.7 ± 35.0

** significantly ($p<0.01$) greater than static head condition.

++ significantly ($p<0.01$) greater than static and dynamic at 0.2m/s.

Table 6.2 The influence of static/dynamic head condition on the centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions, magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), total path length (TL), mediolateral (TLx) and anteroposterior (TLy) path lengths, mean velocity of sway (Vm), mediolateral (Vxm) and anteroposterior (Vym) sway velocities, and angle of sway from the sagittal plane (Ay) (mean ± SD).

Movement of the head at 0.2m/s and 1.0m/s resulted in a significant ($p<0.01$) increase in the magnitude of mediolateral sway, or separately to the right and left, and anteroposterior sway, or separately anteriorly and posteriorly, compared with the static condition. Furthermore, there was a significant ($p<0.01$) increase in Sx, Sr, Sl, Sy, Sa and Sp for head movement at 1.0m/s compared with 0.2m/s. The findings for TL, TLx, TLy, Vm, Vxm and Vym were similar to those observed for the mean mediolateral and anteroposterior sway magnitudes (Table 6.2).

Direction of head movement

The direction of head movement influenced all postural sway parameters except the mediolateral COG projection and the angle of sway from the sagittal plane. As shown in Table 6.3 there was a significant ($p<0.01$) posterior shift in the

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
Y (mm)	1.01 ± 2.55 +	1.21 ± 2.48	0.81 ± 2.59 **

** significantly ($p<0.01$) less than extension and neutral.
+ significantly ($p<0.05$) less than neutral.

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
Y (mm)	0.89 ± 2.49	1.00 ± 2.56	0.77 ± 2.56

Postural sway parameter	Diagonal head movement	
	LE	RE
Y (mm)	1.09 ± 2.54 *	1.00 ± 2.60 *

* significantly ($p<0.01$) greater than horizontal head movement with flexion and vertical head movement with rotation to the right.

Table 6.3 **The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the anteroposterior centre of gravity projection (Y) (mean ± SD).**

COG projection for horizontal head movement with flexion compared with extension and neutral. In addition, with the neck extended a significant posterior shift of the COG projection was observed when compared with the neck in neutral. In contrast, vertical and diagonal head movement had no significant influence on the anteroposterior COG projection. There was, however a significant increase ($p<0.01$) in Y with diagonal head movement compared with horizontal head movement with flexion and vertical movement with rotation to the right.

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
Sx (mm)	1.91 ± 1.44	1.86 ± 1.38	1.71 ± 1.07
Sr (mm)	0.97 ± 0.71	0.96 ± 0.73	0.86 ± 0.55
Sl (mm)	0.95 ± 0.74	0.90 ± 0.67	0.85 ± 0.53

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
Sx (mm)	1.71 ± 1.01	1.55 ± 0.92	1.74 ± 1.06
Sr (mm)	0.86 ± 0.53	0.77 ± 0.46	0.87 ± 0.54
Sl (mm)	0.85 ± 0.50	0.78 ± 0.47	0.87 ± 0.54

Postural sway parameter	Diagonal head movement	
	LE	RE
Sx (mm)	1.50 ± 0.87 * +	1.60 ± 1.00 *
Sr (mm)	0.75 ± 0.44 * +	0.81 ± 0.53 *
Sl (mm)	0.75 ± 0.44 * +	0.79 ± 0.48 *

* significantly ($p<0.01$) less than horizontal head movement with extension.
\+ significantly ($p<0.01$) less than vertical head movement with rotation to the right or left.

Table 6.4 The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude mediolateral sway (Sx) (separately to the right (Sr) and left (Sl)) (mean ± SD).

No differences in Sx, Sr or Sl were observed for any direction of movement (Table 6.4). However, there was a significant decrease ($p<0.01$) in Sx, Sr and Sl for diagonal head movement compared with horizontal head movement with extension. Furthermore, a significant decrease was observed in Sx, Sr and Sl for

LE diagonal head movement compared with vertical head movement with rotation either to the right or left.

There was a significant decrease in Sy for horizontal head movement with the neck neutral or flexed ($p<0.01$) compared with extension: this reduction was due to the significant ($p<0.01$) decrease in Sp (Table 6.5). Significant decreases in Sy were also observed for vertical head movement with rotation either to the right or left compared with looking directly ahead: this reduction was due to the significant decrease in Sp. No difference in Sa was observed. For diagonal head movement no differences were observed in Sy , Sa or Sp (Table 6.5).

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
Sy (mm)	1.48 ± 1.01	1.29 ± 0.78 *	1.22 ± 0.73 **
Sa (mm)	0.72 ± 0.50	0.65 ± 0.41	0.61 ± 0.36
Sp (mm)	0.76 ± 0.53	0.64 ± 0.38 **	0.60 ± 0.37 **

* $p<0.05$, ** $p<0.01$ significantly less than extension.

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
Sy (mm)	1.47 ± 0.82 *	1.57 ± 0.97	1.45 ± 0.84 *
Sa (mm)	0.76 ± 0.45	0.79 ± 0.49	0.74 ± 0.45
Sp (mm)	0.71 ± 0.42 **	0.78 ± 0.49	0.71 ± 0.40 *

* $p<0.05$, ** $p<0.01$ significantly less than looking directly ahead.

Postural sway parameter	Diagonal head movement	
	LE	RE
Sy (mm)	1.33 ± 0.73	1.41 ± 0.84 *
Sa (mm)	0.68 ± 0.39	0.73 ± 0.45 *
Sp (mm)	0.65 ± 0.35	0.68 ± 0.42

* significantly ($p<0.01$) greater than horizontal head movement with flexion.

Table 6.5 The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)) (mean ± SD).

There was, however a significant ($p<0.01$) increase in Sy, due to the significant ($p<0.01$) increase in Sa, with RE diagonal head movement compared with head movement horizontally with the neck flexed (Figure 6.5).

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
TL (mm)	132.3 ± 64.3 **	124.4 ± 59.7	115.7 ± 38.4
TLx (mm)	85.3 ± 46.2 *	82.1 ± 45.2	76.1 ± 29.2
TLy (mm)	81.0 ± 37.4 **	73.8 ± 30.9	68.8 ± 21.5

** significantly ($p<0.01$) greater than flexion.

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
TL (mm)	119.7 ± 43.8	117.3 ± 42.4	124.2 ± 49.5
TLx (mm)	76.1 ± 32.3 *	71.2 ± 29.3	79.6 ± 36.1 *
TLy (mm)	74.4 ± 25.1	75.6 ± 27.6	76.2 ± 28.1

* significantly ($p<0.05$) greater than looking directly ahead.

Postural sway parameter	Diagonal head movement	
	LE *	RE *
TL (mm)	110.4 ± 40.6 ++	115.5 ± 40.2
TLx (mm)	70.1 ± 30.3 +	72.3 ± 27.2
TLy (mm)	68.2 ± 22.4 ++	72.6 ± 25.5

* significantly ($p<0.01$) less than horizontal head movement with extension and vertical head movement with rotation to the right.

+ $p<0.05$, ++ $p<0.01$ significantly less than vertical head movement with rotation to the left.

Table 6.6 The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the total path length (TL) and path length in the mediolateral (TLx) and anteroposterior (TLy) directions (mean ± SD).

As shown Table 6.6 a significant ($p<0.01$) increase in TL, due to the significant increase in both TLx and TLy ($p<0.01$), was observed for horizontal head movement with extension compared with flexion, there being no difference in neutral. For vertical head movement (Table 6.6) there was a significant increase in TLx with rotation either to the right or left compared with looking directly ahead. In contrast, no difference in TL or TLy was observed. For diagonal head movements (Table 6.6) no differences in TL, TLx or TLy were observed. There was a significant ($p<0.01$) reduction in TL, TLx and TLy for both diagonal head movements compared with horizontal head movement with extension or vertical head movement with rotation to the right. There was a significant decrease in TL ($p<0.01$), TLx and TLy ($p<0.01$) for LE diagonal head movement compared with vertical head movement with rotation to the left.

Table 6.7 shows that the differences observed for the velocity of sway and the mediolateral and anteroposterior sway velocities were similar to those observed with respect to path length and the mediolateral and anteroposterior path lengths.

Postural sway parameter	**Horizontal head movement**		
	Extension	**Neutral**	**Flexion**
Vm (mm/s)	6.64 ± 3.23 **	6.42 ± 3.00	5.80 ± 1.93
Vxm (mm/s)	4.28 ± 2.32 *	4.12 ± 2.27	3.81 ± 1.47
Vym (mm/s)	4.06 ± 1.88 **	3.69 ± 1.57	3.45 ± 1.08

** significantly ($p<0.01$) greater than flexion.

Postural sway parameter	**Vertical head movement**		
	Left	**Looking ahead**	**Right**
Vm (mm/s)	6.00 ± 2.20	5.88 ± 2.13	6.23 ± 2.49
Vxm (mm/s)	3.81 ± 1.62 *	3.57 ± 1.74	3.99 ± 1.81 *
Vym (mm/s)	3.73 ± 1.26	3.78 ± 1.40	3.82 ± 1.41

* significantly ($p<0.05$) greater than looking directly ahead.

Postural sway parameter	**Diagonal head movement**	
	LE *	**RE** *
Vm (mm/s)	5.54 ± 2.04 ++	5.64 ± 2.15
Vxm (mm/s)	3.52 ± 1.52 +	3.62 ± 1.37
Vym (mm/s)	3.41 ± 1.14 ++	3.63 ± 1.30

* significantly ($p<0.01$) less than horizontal head movement with extension and vertical head movement with rotation to the right.

+ $p<0.05$, ++ $p<0.01$ significantly less than vertical head movement with rotation to the left.

Table 6.7 **The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the mean velocity of sway (Vm) and mean sway velocity in the mediolateral (Vxm) and anteroposterior (Vym) directions (mean ± SD).**

Interaction between static/dynamic head condition and direction of head movement

The analyses of variance showed significant interactions between static/dynamic head condition and the direction of head movement for all of sway parameters except X, Sl and Ay.

A significant ($p<0.01$) posterior shift of the COG projection for horizontal head movement either static or moving at 0.2m/s was observed with the neck extended or flexed compared with neutral. With head movement at 1.0m/s there was a significant ($p<0.01$) posterior shift of the COG projection with neck flexion compared with neutral and extension (Table 6.8).

Postural sway parameter	Head condition	Horizontal head movement		
		Extension	Neutral	Flexion
Y(mm)	Static	2.07 ± 2.61 *	2.20 ± 2.59	2.06 ± 2.71 *
	0.2 m/s	0.31 ± 2.42 **	0.85 ± 2.39	0.27 ± 2.36 **
	1.0 m/s	0.64 ± 2.41	0.59 ± 2.30	0.11 ± 2.38 ++

* $p<0.05$, ** $p<0.01$ significantly less than neutral.
++ significantly ($p<0.01$) less than extension and neutral.

Postural sway parameter	Head condition	Vertical head movement		
		Left	Looking ahead	Right
Y(mm)	Static	2.05 ± 2.67 **	2.29 ± 2.62	1.99 ± 2.62 **
	0.2 m/s	0.23 ± 2.25	0.31 ± 2.23	0.20 ± 2.44
	1.0 m/s	0.38 ± 2.24	0.41 ± 2.44	0.12 ± 2.32

** significantly ($p<0.01$) less than looking directly ahead.

Postural sway parameter	Head condition	Diagonal head movement	
		LE	RE
Y(mm)	Static	2.25 ± 2.57	2.23 ± 2.61
	0.2 m/s	0.45 ± 2.43	0.37 ± 2.51
	1.0 m/s	0.57 ± 2.36	0.38 ± 2.38

Table 6.8 The interaction between static/dynamic head condition and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the anteroposterior centre of gravity projection (Y) (mean ± SD).

For vertical head movement (Table 6.8) there was a significant ($p<0.01$) posterior shift of the COG projection for the static head condition with rotation to the right or left compared with looking directly ahead. No difference in Y was observed for either velocity of movement. As shown in Table 6.8 there were no differences in Y associated with diagonal head movements.

For the static head condition there was a significant ($p<0.01$) anterior shift of the COG projection with both diagonal head movements compared with horizontal head movement with extension or flexion and vertical head movement with rotation to the right or left. At 0.2m/s no differences were observed with diagonal head movement compared with horizontal or vertical movements. At 1.0m/s there was a significant anterior shift of the COG projection with diagonal head movement compared with horizontal head movement with flexion and vertical head movement with rotation to the right (Table 6.8).

No differences were observed for Sx or Sr for any direction of head movement for either the static or dynamic conditions (Table 6.9). However, at 0.2m/s there was a significant reduction in Sx and Sr for both diagonal head movements compared with horizontal head movement with neck extension. In addition, a significant decrease in Sx ($p<0.01$) and Sr was observed for LE diagonal head movement compared with vertical head movement with rotation to the left. At the higher velocity there was also a significant reduction in Sx and Sr for LE diagonal head movement compared with horizontal head movement with extension and vertical movement with rotation to the left.

As shown in Table 6.10 no significant differences were observed in Sy, Sa or Sp for the horizontal static head. In contrast, at the lower velocity there was a significant increase in Sy with neck extension compared with neutral, due to the significant increase in Sa and Sp, and neck flexion, due to the significant increase in Sp. At the higher velocity with neck extension a significant increase in Sy, Sa and Sp ($p<0.01$) was observed compared with flexion, but not with the neck neutral.

Postural sway parameter	Head condition	Horizontal head movement		
		Extension	Neutral	Flexion
Sx (mm)	Static	0.65 ± 0.19	0.67 ± 0.20	0.69 ± 0.20
	0.2 m/s	2.19 ± 0.73	1.88 ± 0.69	1.94 ± 0.70
	1.0 m/s	2.90 ± 1.76	3.04 ± 1.57	2.51 ± 1.08
Sr (mm)	Static	0.32 ± 0.09	0.33 ± 0.10	0.33 ± 0.09
	0.2 m/s	1.13 ± 0.42	0.96 ± 0.38	0.99 ± 0.41
	1.0 m/s	1.44 ± 0.83	1.57 ± 0.82	1.25 ± 0.55

Postural sway parameter	Head condition	Vertical head movement		
		Left	Looking ahead	Right
Sx (mm)	Static	0.70 ± 0.22	0.63 ± 0.15	0.68 ± 0.24
	0.2 m/s	2.10 ± 0.89	1.75 ± 0.54	2.00 ± 0.73
	1.0 m/s	2.33 ± 0.85	2.27 ± 0.90	2.54 ± 0.99
Sr (mm)	Static	0.35 ± 0.12	0.30 ± 0.06	0.33 ± 0.11
	0.2 m/s	1.10 ± 0.52	0.86 ± 0.26	0.98 ± 0.33
	1.0 m/s	1.14 ± 0.40	1.13 ± 0.46	1.29 ± 0.51

Postural sway parameter	Head condition	Diagonal head movement	
		LE	RE
Sx (mm)	Static	0.66 ± 0.18	0.66 ± 0.20
	0.2 m/s	1.69 ± 0.71	1.79 ± 0.92
	1.0 m/s	2.15 ± 0.77	2.36 ± 0.82
Sr (mm)	Static	0.33 ± 0.09	0.32 ± 0.09
	0.2 m/s	0.84 ± 0.36	0.91 ± 0.54
	1.0 m/s	1.10 ± 0.38	1.20 ± 0.40

Table 6.9 **The interaction between static/dynamic head condition and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of sway in the mediolateral direction (Sx) and to the right (Sr) (mean ± SD).**

For vertical head movement (Table 6.10) in the static head condition there was a significant increase Sy ($p<0.01$), Sa and Sp ($p<0.01$) with rotation to the left compared with looking directly ahead or rotation to the right. No significant differences in Sy, Sa or Sp were observed at the lower velocity of head movement, however at the higher velocity there was a significant reduction in Sy with rotation to the right ($p<0.01$) and left compared with looking directly ahead, the reduction being due to the significant ($p<0.01$) decrease in Sp.

Postural sway parameter	Head condition	Horizontal head movement		
		Extension	Neutral	Flexion
Sy (mm)	Static	0.55 ± 0.16	0.55 ± 0.17	0.56 ± 0.18
	0.2 m/s	1.73 ± 0.65	1.37 ± 0.49 *	1.40 ± 0.38 *
	1.0 m/s	2.17 ± 1.13	1.94 ± 0.76	1.69 ± 0.86 *
Sa (mm)	Static	0.28 ± 0.08	0.27 ± 0.09	0.28 ± 0.09
	0.2 m/s	0.84 ± 0.34	0.70 ± 0.25 *	0.72 ± 0.20
	1.0 m/s	1.03 ± 0.57	0.98 ± 0.43	0.83 ± 0.43 *
Sp (mm)	Static	0.27 ± 0.08	0.27 ± 0.09	0.28 ± 0.09
	0.2 m/s	0.89 ± 0.36	0.67 ± 0.25 *	0.68 ± 0.20 *
	1.0 m/s	1.14 ± 0.58	0.97 ± 0.35	0.85 ± 0.45 **

* $p<0.05$, ** $p<0.01$ significantly less than extension.

Postural sway parameter	Head condition	Vertical head movement		
		Left	Looking ahead	Right
Sy (mm)	Static	0.59 ± 0.19 ++	0.52 ± 0.15	0.55 ± 0.18
	0.2 m/s	1.56 ± 0.51	1.58 ± 0.39	1.51 ± 0.43
	1.0 m/s	2.26 ± 0.57 *	2.62 ± 0.64	2.28 ± 0.63 **
Sa (mm)	Static	0.30 ± 0.09 +	0.26 ± 0.08	0.27 ± 0.08
	0.2 m/s	0.83 ± 0.34	0.81 ± 0.23	0.78 ± 0.24
	1.0 m/s	1.16 ± 0.31	1.30 ± 0.32	1.16 ± 0.36
Sp (mm)	Static	0.30 ± 0.10 ++	0.25 ± 0.07	0.27 ± 0.09
	0.2 m/s	0.73 ± 0.26	0.77 ± 0.18	0.73 ± 0.20
	1.0 m/s	1.10 ± 0.34 **	1.31 ± 0.35	1.12 ± 0.30 **

+ $p<0.05$, ++ $p<0.01$ significantly greater than looking directly ahead and rotation to the right.
* $p<0.05$, ** $p<0.01$ significantly less than looking directly ahead.

Postural sway parameter	Head condition	Diagonal head movement	
		LE	RE
Sy (mm)	Static	0.55 ± 0.18	0.53 ± 0.18
	0.2 m/s	1.46 ± 0.61	1.42 ± 0.43
	1.0 m/s	1.97 ± 0.43	2.27 ± 0.62
Sa (mm)	Static	0.28 ± 0.09	0.27 ± 0.09
	0.2 m/s	0.74 ± 0.33	0.71 ± 0.23
	1.0 m/s	1.01 ± 0.26	1.21 ± 0.32
Sp (mm)	Static	0.28 ± 0.10	0.27 ± 0.09
	0.2 m/s	0.72 ± 0.28	0.71 ± 0.21
	1.0 m/s	0.96 ± 0.19	1.07 ± 0.38

Table 6.10 **The interaction between static/dynamic head condition and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of anteroposterior sway (Sy), (separately anteriorly (Sa) and posteriorly (Sp)) (mean ± SD).**

Again for diagonal head movement (Table 6.10) no significant differences were observed. However, for the static head condition there was a significant ($p<0.01$) increase in Sy, due to the significant increase in Sp, for RE diagonal head movement compared with horizontal head movement with flexion. Furthermore, a significant ($p<0.01$) decrease in Sy, Sa and Sp with both diagonal head movements compared with vertical head movement with rotation to the left was observed. At the lower velocity there was a significant reduction in Sy, due to the decrease in Sp, for both diagonal head movements compared with horizontal head movement with extension. At the higher velocity a significant ($p<0.01$) increase in Sy, due to the significant ($p<0.01$) increase in Sa, was observed for RE diagonal head movement compared with horizontal head movement with flexion.

As shown in Table 6.11 no significant differences were observed in TL, TLx and TLy for the static horizontal head condition. At the lower velocity of movement there was a significant increase in TL with neck extension compared with neutral, due to the significant increase in TLx and TLy, and flexion, due to the significant ($p<0.01$) increase in TLy. At the higher velocity a significant increase in TL ($p<0.01$), TLx and TLy ($p<0.01$) with neck extension compared with flexion was observed, but there was no difference between extension and neutral. There were no differences in TL, TLx and TLy for vertical or diagonal head movements for any condition (Table 6.11).

In the static head condition no differences were observed in TL, TLx and TLy between diagonal, horizontal or vertical head movements. At the lower velocity there was a significant ($p<0.01$) decrease in TL, TLx and TLy with both diagonal head movements compared with horizontal head movement with neck extension. At the higher velocity a significant ($p<0.01$) reduction in TL was observed for LE diagonal head movement compared with horizontal head movement with neck extension, due to the significant decrease in TLx ($p<0.01$) and TLy, and vertical head movement with rotation to the right, due to the significant decrease in TLx and TLy ($p<0.01$).

A similar pattern for Vm, Vxm and Vym was observed with respect to TL, TLx and TLy (Table 6.12).

Postural sway parameter	Head condition	Horizontal head movement		
		Extension	Neutral	Flexion
TL (mm)	Static	84.1 ± 14.5	84.3 ± 14.0	85.0 ± 14.0
	0.2 m/s	136.8 ± 37.4	119.2 ± 32.7 *	120.7 ± 30.9 *
	1.0 m/s	176.1 ± 82.6	169.7 ± 77.3	141.2 ± 41.9 **
TLx (mm)	Static	51.5 ± 9.51	51.5 ± 8.67	52.1 ± 8.61
	0.2 m/s	87.0 ± 25.6	77.2 ± 21.4 *	79.7 ± 24.1
	1.0 m/s	117.4 ± 60.1	117.7 ± 59.2	96.4 ± 30.9 *
TLy (mm)	Static	53.2 ± 9.05	53.5 ± 9.32	53.6 ± 9.35
	0.2 m/s	85.4 ± 25.2	72.1 ± 22.1 *	71.3 ± 16.9 **
	1.0 m/s	104.4 ± 47.3	95.9 ± 38.1	81.5 ± 25.5 **

* $p<0.05$, ** $p<0.01$ significantly less than extension.

Postural sway parameter	Head condition	Vertical head movement		
		Left	Looking ahead	Right
TL (mm)	Static	85.7 ± 14.5	82.6 ± 13.0	85.1 ± 15.5
	0.2 m/s	122.8 ± 44.3	116.5 ± 28.4	126.8 ± 39.5
	1.0 m/s	150.5 ± 39.5	152.8 ± 45.1	160.7 ± 53.1
TLx (mm)	Static	52.6 ± 9.24	50.1 ± 8.11	52.3 ± 9.88
	0.2 m/s	80.0 ± 33.9	73.6 ± 24.2	82.0 ± 28.5
	1.0 m/s	95.5 ± 32.0	90.0 ± 34.3	104.3 ± 41.4
TLy (mm)	Static	54.0 ± 9.47	52.6 ± 8.53	53.7 ± 9.93
	0.2 m/s	74.7 ± 23.8	72.3 ± 13.4	77.1 ± 23.8
	1.0 m/s	94.4 ± 21.0	102.0 ± 28.4	97.9 ± 27.6

Postural sway parameter	Head condition	Diagonal head movement	
		LE	RE
TL (mm)	Static	84.1 ± 14.4	83.7 ± 13.6
	0.2 m/s	111.3 ± 42.0	115.6 ± 40.0
	1.0 m/s	135.9 ± 41.9	147.1 ± 33.6
TLx (mm)	Static	51.1 ± 8.91	51.3 ± 8.10
	0.2 m/s	71.3 ± 29.4	72.6 ± 28.1
	1.0 m/s	88.0 ± 34.6	93.0 ± 23.1
TLy (mm)	Static	53.6 ± 9.51	53.0 ± 8.75
	0.2 m/s	68.3 ± 24.6	72.3 ± 25.1
	1.0 m/s	82.8 ± 20.4	92.5 ± 22.4

Table 6.11 **The interaction between static/dynamic head condition and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the total path length (TL) and path length in the mediolateral (TLx) and anteroposterior (TLy) directions (mean ± SD).**

Postural sway parameter	Head condition	Horizontal head movement		
		Extension	Neutral	Flexion
Vm (mm/s)	Static	4.21 ± 0.73	4.22 ± 0.70	4.25 ± 0.70
	0.2 m/s	6.87 ± 1.88	5.98 ± 1.64 *	6.06 ± 1.55 *
	1.0 m/s	8.83 ± 4.14	8.51 ± 3.88	7.09 ± 2.10 **
Vxm (mm/s)	Static	2.57 ± 0.48	2.57 ± 0.43	2.61 ± 0.43
	0.2 m/s	4.37 ± 1.28	3.87 ± 1.07 *	4.00 ± 1.21
	1.0 m/s	5.91 ± 2.97	5.89 ± 3.02	4.84 ± 1.55 *
Vym (mm/s)	Static	2.66 ± 0.45	2.64 ± 0.54	2.68 ± 0.47
	0.2 m/s	4.28 ± 1.26	3.62 ± 1.11 *	3.58 ± 0.85 **
	1.0 m/s	5.24 ± 2.37	4.81 ± 1.91	4.09 ± 1.28 **

* $p<0.05$, ** $p<0.01$ significantly less than extension.

Postural sway parameter	Head condition	Vertical head movement		
		Left	Looking ahead	Right
Vm (mm/s)	Static	4.28 ± 0.73	4.13 ± 0.65	4.26 ± 0.77
	0.2 m/s	6.16 ± 2.23	5.84 ± 1.42	6.36 ± 1.98
	1.0 m/s	7.55 ± 1.98	7.67 ± 2.26	8.06 ± 2.66
Vxm (mm/s)	Static	2.63 ± 0.46	2.51 ± 0.41	2.62 ± 0.49
	0.2 m/s	4.01 ± 1.70	3.69 ± 1.21	4.12 ± 1.43
	1.0 m/s	4.79 ± 1.60	4.52 ± 1.72	5.23 ± 2.08
Vym (mm/s)	Static	2.70 ± 0.47	2.59 ± 0.51	2.68 ± 0.50
	0.2 m/s	3.75 ± 1.19	3.63 ± 0.67	3.87 ± 1.19
	1.0 m/s	4.74 ± 1.06	5.12 ± 1.42	4.91 ± 1.39

Postural sway parameter	Head condition	Diagonal head movement	
		LE	RE
Vm (mm/s)	Static	4.20 ± 0.72	4.19 ± 0.64
	0.2 m/s	5.58 ± 2.11	5.80 ± 2.00
	1.0 m/s	6.82 ± 2.10	7.38 ± 1.69
Vxm (mm/s)	Static	2.55 ± 0.04	2.56 ± 0.04
	0.2 m/s	3.58 ± 1.48	3.64 ± 1.41
	1.0 m/s	4.42 ± 1.74	4.67 ± 1.16
Vym (mm/s)	Static	2.64 ± 0.06	2.61 ± 0.05
	0.2 m/s	3.43 ± 1.24	3.63 ± 1.26
	1.0 m/s	4.15 ± 1.02	4.64 ± 1.12

Table 6.12 The interaction between static/dynamic head condition and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the mean velocity of sway (Vm) and mean sway velocity in the mediolateral (Vxm) and anteroposterior (Vym) directions (mean ± SD).

Interaction between sex, static/dynamic head condition and direction of head movement with various neck positions

The analyses of variance showed a significant interaction between sex, static/dynamic head condition and the direction of head movement for X only. As shown in Table 6.13 no differences were observed for either females or males for the horizontal static or dynamic condition.

Postural sway parameter	Head condition	Horizontal head movement		
		Extension	Neutral	Flexion
Females	Static	3.05 ± 2.07	2.98 ± 2.46	2.66 ± 2.45
X (mm)	0.2 m/s	4.09 ± 2.14	4.20 ± 2.24	4.19 ± 2.05
	1.0 m/s	4.27 ± 2.24	4.32 ± 2.23	4.22 ± 1.96
Males	Static	1.09 ± 1.54	1.07 ± 1.52	1.26 ± 1.37
X (mm)	0.2 m/s	2.21 ± 2.08	2.39 ± 1.94	1.89 ± 2.01
	1.0 m/s	2.27 ± 2.27	2.29 ± 1.90	2.50 ± 2.01

Postural sway parameter	Head condition	Vertical head movement		
		Left	Looking ahead	Right
Females	Static	2.87 ± 2.60	2.77 ± 1.99	3.05 ± 2.24
X (mm)	0.2 m/s	4.12 ± 2.16 *	3.78 ± 2.19	4.25 ± 1.95 *
	1.0 m/s	4.20 ± 2.15	4.06 ± 2.13	4.11 ± 2.25
Males	Static	1.32 ± 1.19	1.02 ± 1.69	1.09 ± 1.58
X (mm)	0.2 m/s	2.31 ± 1.96	2.76 ± 2.20	2.31 ± 2.11
	1.0 m/s	1.73 ± 1.77 ++	2.32 ± 1.95	2.28 ± 1.80

* significantly ($p<0.05$) greater than looking directly ahead.

++ significantly ($p<0.01$) less than looking direct ahead and rotation to the right.

Postural sway parameter	Head condition	Diagonal head movement	
		LE	RE
Females	Static	2.71 ± 2.62	2.73 ± 2.27
X (mm)	0.2 m/s	3.93 ± 2.07	4.01 ± 2.00
	1.0 m/s	4.31 ± 2.37	3.90 ± 2.29
Males	Static	1.01 ± 1.54	1.17 ± 1.28
X (mm)	0.2 m/s	2.07 ± 1.76	2.16 ± 1.54
	1.0 m/s	2.09 ± 1.53	2.06 ± 1.74

Table 6.13 **The interaction between sex, static/dynamic head condition and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the mediolateral centre of gravity projection (X) (mean ± SD).**

For vertical head movement there was no difference in X with for the static condition for both females and males. However, there was a significant shift in the mediolateral COG projection to the right in females for the lower velocity with rotation either to the right or left compared with looking directly ahead: in contrast, there was no difference in males. For the higher velocity no difference was observed for females, however, there was a significant ($p<0.01$) shift in the mediolateral COG projection to the left in males for rotation to the left compared with looking directly ahead and rotation to the right. No differences were observed for diagonal head movement for both females and males irrespective of the velocity of head movement. In addition, no differences were observed between head movement diagonally, horizontally or vertically for any static/dynamic head condition.

6.4 Discussion

As for the subject characteristics in Experiments 1 (Chapter4) and 2 (Chapter 5), there was no difference in age but there were significant differences in height, foot length and therefore eye level height and eye-object distance between males and females.

Sex was observed to influence the COG projection in the mediolateral direction. The finding from the interaction between sex, head condition and direction of head movement indicates that the change in the mediolateral COG projection in females is due to vertical head movement with the neck rotated either to the right or left at the lower velocity of head movement. It is suggested that the neck proprioceptive system leads to a decrease in postural control in the mediolateral direction in females. In males the shift of the mediolateral COG projection is seen at the higher velocity; it is therefore suggested that the fluctuation is under the control of the interaction between the vestibular and neck proprioceptive systems.

During standing the various head conditions were observed to have an influence on most postural sway parameters. The mediolateral COG projection, but not the anteroposterior, is clearly influenced by head condition. It is postulated that movement of the head during standing with the feet together may have an additive effect with the lower limb proprioceptive input in controlling mediolateral sway. The postural instability induced by head movement appears to be dependent on the velocity of movement. The difference of head condition, static or dynamic, on postural control will be due to the difference in responses to static or dynamic stimulation of the vestibular and neck proprioceptor systems. In animal experiments vestibular neurones are able to distinguish between passive and active head movement (McCrea et al. 1999). It is feasible that vestibular and neck propriceptive neurones may also play a different role in the response to static and dynamic stimulation in humans.

The direction of head movement has also been observed to have an influence on most postural sway parameters. Horizontal head movement with neck extension causes postural instability and appears to cause a posterior shift of the body. Neck extension has been demonstrated to increase postural sway (Brandt et al. 1981) because of the disadvantageous position of the utricles (Jackson and Epstein 1991). The findings in these experiments show a difference in response between neck extension and flexion. The vestibular system has been reported to depolarise during neck extension but hyperpolarise during neck flexion (Livingston 1990; Sherwood 1997). It is, therefore possible that there are different mechanisms of vestibular input during neck extension and flexion on postural control. There is a difference between horizontal static and dynamic head movement associated with neck extension for most postural sway parameters. In the static condition there is no difference between neck flexion, extension or neutral for any sway parameter, except the anteroposterior COG projection. However, postural sway behaviour deteriorates when the neck is extended during head movement. The increase in postural instability leads to a shift of the COG projection anteriorly or posteriorly. It may be that the vestibular system is always activated but that it is not able to achieve a state of equilibrium.

Vertical head movement with neck rotation to the right or left leads to postural stabilisation by reducing the magnitude of sway in the posterior direction.

With rotation to the right or left compared with looking directly ahead, although there is no increase in the magnitude of mediolateral sway, this appears to enhance the total path length and velocity of sway in the mediolateral direction. It is, therefore suggested that asymmetrical neck input helps to stabilise posture in the sagittal plane and destabilise it in the mediolateral direction by increasing path length and sway velocity. The difference between static and dynamic vertical head movement indicates that the vestibular system assists neck proprioception in stabilising anteroposterior magnitude sway, since there is a reduction of the magnitude of anteroposterior sway, particularly posteriorly, during head movement at the higher velocity. There was no change in the mediolateral path length and sway velocity for the static head condition or at either velocity of head movement, suggesting that the interaction between vestibular and neck proprioception stabilises posture in the anteroposterior direction.

Diagonal head movement shows greater postural stability than horizontal head movement with extension but the less than with flexion. It also shows a greater postural stabilisation than vertical head movement with rotation to the right or left. It is suggested that neck proprioceptor input reduces the destabilising effect of the vestibular input with neck extension, but disturbs it with neck flexion. It also shows that the vestibular input supports neck proprioceptor input in postural control leading to postural stabilisation. The difference between the static and dynamic head conditions confirms this role of the vestibular system with neck proprioception.

6.5 Summary

There is a difference in postural sway behaviour in response to static and dynamic vestibular, as well as neck proprioceptor, stimulation. Dynamic vestibular stimulation leads to postural destabilisation, while dynamic neck proprioception stabilises posture in the anteroposteriorly but destabilises it mediolaterally. The vestibular-neck proprioceptive interaction leads to reduced anteroposterior sway magnitude, with the vestibular input appearing to support the stabilising effect of neck proprioception.

Chapter 7

Experiment 3: Responses to static visual, vestibular, neck proprioceptor and auditory stimulation

7.1 Introduction

Evidence from previous experiments confirms that postural sway behaviour is influenced by sensory input, either individually or in combination, from the visual, vestibular and neck proprioceptor systems. One function of these systems is to provide information about head position (Guitton et al. 1986; Pozzo et al. 1990; Smetanin et al. 1993; Karnath et al. 1994; Kanaya et al. 1995). The auditory system has also been shown to have an influence on postural maintenance (Juntunen et al. 1987; Raper and Soames 1991; Kilburn et al. 1992; Soames and Raper 1992; Sakellari and Soames 1996). In some conditions of postural control an interaction between vision and auditory system has been observed (Sakellari and Soames 1996) but in others these appear to be no interaction (Raper and Soames 1991; Soames and Raper 1992). Thus, the interaction between vision and auditory information is not clear. The interaction between the auditory system and either the vestibular or neck proprioceptor systems in postural control has not been investigated. Thus, in this experiment both the individual sensory components and the interactions of the visual, vestibular, neck proprioceptor and auditory inputs on postural sway behaviour under condition of static stimulation is investigated.

7.2 Materials and methods

Thirty healthy subjects (15 females, 15 males), aged between 18 and 30 years, participated in the experiment.

A total 36 measurements; looking directly ahead (A), or with neck rotation 45^0 to the right (R) and left (L), each with the neck in neutral (N), flexed (F) or extended (E) 45^0 with the eyes open (O) and closed (C) at sound frequencies

1595Hz and 2916Hz, were taken for each subject. The recordings of postural sway behaviour were taken with the subject standing comfortably erect with the feet together on the force platform after they had been instructed to look at and focus on a specific marker placed on the screen (further details are given in Chapter 3 part 3.7.3).

Five-way analyses of variance were conducted on each of the sway parameters (Chapter 3 part 3.3) with sex, vision, neck rotation (looking directly ahead/right /left) and neck flexion/extension (neutral/flexion/extension) and sound frequency as independent variables in order to determine the influence of each on postural sway behaviour. t-tests were conducted as appropriate to determine the differences between the independent variables influencing each postural sway parameter. Unless otherwise stated all differences are at the 5% level of significance.

7.3 Results

7.3.1 Subject characteristics

The characteristics of the population studied are given in Table 7.1, with the data being presented for the whole group, as well as for the females and males separately. There was no difference in age between females and males, however height, foot length and eye level height were significantly ($p<0.01$) greater and eye-object distance was significantly ($p<0.01$) smaller in males.

7.3.2 Analyses of variance

The analyses of variance showed significant differences for vision, sound, neck rotation and neck flexion/extension as well as their interactions on postural sway behaviour. Although there was no difference between the sexes in postural sway behaviour, interactions between sex and other variables were observed (Appendix 8).

Subject characteristics	All	Females	Males
Age (year)	24.1 ± 4.11	25.3 ± 3.88	23.1. ± 4.33
Height (cm)	167.5 ± 10.5	160.4 ± 8.81	174.5 ± 6.63 **
Foot length (cm)	24.6 ± 1.65	23.5 ± 0.90	25.7 ± 1.50 **
Eye-Object distance (cm)	48.9 ± 1.65	50.0± 0.90	47.8 ± 1.50 **
Eye level height (cm)	157.1 ± 10.5	150.3 ± 8.85	163.9 ± 7.02 **

** significantly ($p<0.01$) greater or less than female value.

Table 7.1 The characteristics the subjects (15 females, 15 males) who participated in Experiment 3 (mean ± SD).

Vision

The loss of vision, i.e. standing with the eyes closed, influenced most postural sway parameters. As shown in Table 7.2 the mediolateral COG was significantly ($p<0.01$) closer to the midline position when standing with eyes closed than with eyes open, however, no difference was observed with respect to the anteroposterior COG projection. Both the mean magnitude of mediolateral and anteroposterior sway significantly ($p<0.01$) increased when standing with eyes closed compared with eyes open. In addition, the total path length and the mean velocity of sway, including those in the mediolateral and anteroposterior directions separately, also significantly ($p<0.01$) increased without visual feedback. There was no difference in Ay when standing with eyes closed compared with eyes open.

Sound

The analyses of variance showed that the frequency of sound only influenced the magnitude of mediolateral sway, as well as separately to the right and the left. As shown in Table 7.3 there was a significant ($p<0.01$) increase in Sx, Sr and Sl at 2916Hz compared with 1595Hz.

Postural sway parameter	Vision	
	Eyes open	Eyes closed
X (mm)	3.39 ± 2.48	3.23 ± 2.55 **
Y (mm)	0.07 ± 2.01	0.08 ± 1.93
Sx (mm)	1.16 ± 0.57	1.59 ± 0.67 **
Sr (mm)	0.59 ± 0.33	0.80 ± 0.35 **
Sl (mm)	0.58 ± 0.26	0.80 ± 0.36 **
Sy (mm)	0.91 ± 0.37	1.26 ± 0.51 **
Sa (mm)	0.45 ± 0.19	0.63 ± 0.29 **
Sp (mm)	0.46 ± 0.20	0.64 ± 0.25 **
TL (mm)	173.9 ± 128.6	217.5 ± 129.3 **
TLx (mm)	99.6 ± 80.6	127.6 ± 75.4 **
TLy (mm)	106.2 ± 84.1	134.0 ± 89.8 **
Vm (mm/s)	8.72 ± 6.45	10.9 ± 6.49 **
Vxm (mm/s)	5.01 ± 4.03	6.40 ± 3.79 **
Vym (mm/s)	5.33 ± 4.22	6.73 ± 4.51 **
Ay (°)	-16.0 ± 50.0	-11.8 ± 42.1

** significantly ($p<0.01$) greater than with eyes open.

Table 7.2 **The influence of vision on the centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions, magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), total path length (TL), mediolateral (TLx) and anteroposterior (TLy) path lengths, mean velocity of sway (Vm), mediolateral (Vxm) and anteroposterior (Vym) sway velocities, and angle of sway from the sagittal plane (Ay) (mean ± SD).**

Postural sway parameter	Frequency	
	1595 Hz	2916 Hz
Sx (mm)	1.31 ± 0.57	1.45 ± 0.73 **
Sr (mm)	0.66 ± 0.32	0.73 ± 0.39 **
Sl (mm)	0.65 ± 0.29	0.72 ± 0.37 **

** significantly ($p<0.01$) greater than at frequency 1595Hz.

Table 7.3 **The influence of sound on the magnitude of mediolateral sway (Sx) (separately to the right (Sr) and left (Sl)) (mean ± SD).**

Neck rotation

Neck rotation to the right or left had a significant influence on X, TLx and Vxm only. As shown in Table 7.4 there was a significant shift ($p<0.01$) of the mediolateral COG projection with neck rotation to the left or right compared with looking directly ahead. Rotation to the right and left also showed significant ($p<0.01$) differences. In addition, there was a significant ($p<0.01$) increase in TLx and Vxm with rotation to the right compared with when looking directly ahead or rotation to the left.

Postural sway parameter	Neck rotation		
	Left	Looking ahead	Right
X (mm)	3.16 ± 2.49 **	3.31 ± 2.51	3.46 ± 2.54 ** ++
TLx (mm)	107.9 ± 55.9	108.4 ± 67.3	124.5 ± 105.1 ** ++
Vxm (mm/s)	5.44 ± 2.76	5.44 ± 3.38	6.25 ± 5.28 ** ++

** significantly ($p<0.01$) greater or less than looking directly ahead.
++ significantly ($p<0.01$) greater than rotation to the left.

Table 7.4 The influence of neck rotation on the mediolateral direction as seen in the centre of gravity projection (X), total path length (TLx) and mean velocity of sway (Vxm) (mean ± SD).

Neck flexion/extension

Neck flexion/extension had a significant influence on most sway behaviour parameters except the mean COG projection (Table 7.5). There were significant ($p<0.01$) increases in Sx, Sr, Sl, Sy, Sa and Sp with neck extension compared with neutral. However, there was also a significant ($p<0.01$) increase in Sa with flexion compared with neutral. There was also a significant ($p<0.01$) increase in Sy with extension compared with flexion, due to the increase in Sp.

There were significant increases in TL ($p<0.01$), TLx ($p<0.01$) and TLy with extension compared with neutral or flexion. Similarly, there were significant ($p<0.01$) increases in Vm, Vxm and Vym with extension compared with neutral or flexion.

There was significant ($p<0.01$) decrease in Ay with extension when compared with neutral and flexion.

Postural sway parameter	Neck flexion/extension		
	Extension	Neutral	Flexion
X (mm)	3.32 ± 2.48	3.32 ± 2.53	3.29 ± 2.54
Y (mm)	0.12 ± 1.90	0.06 ± 1.99	0.05 ± 2.01
Sx (mm)	1.43 ± 0.72 **	1.32 ± 0.66	1.38 ± 0.59
Sr (mm)	0.72 ± 0.39 **	0.66 ± 0.36	0.69 ± 0.32
Sl (mm)	0.71 ± 0.35 **	0.66 ± 0.34	0.69 ± 0.31
Sy (mm)	1.14 ± 0.53 ** ++	1.05 ± 0.46	1.08 ± 0.44
Sa (mm)	0.56 ± 0.28 **	0.52 ± 0.24	0.54 ± 0.26 **
Sp (mm)	0.58 ± 0.28 ** ++	0.53 ± 0.24	0.53 ± 0.21
TL (mm)	203.2 ± 133.9 ** ++	193.0 ± 135.5	190.8 ± 122.5
TLx (mm)	119.6 ± 82.6 ** ++	111.1 ± 84.5	110.1 ± 69.8
TLy (mm)	123.7 ± 87.1 * +	119.1 ± 91.6	117.5 ± 85.4
Vm (mm/s)	10.19 ± 6.72 ** ++	9.68 ± 6.80	9.58 ± 6.15
Vxm (mm/s)	6.00 ± 4.14 ** ++	5.60 ± 4.21	5.53 ± 3.50
Vym (mm/s)	6.21 ± 4.37 * +	5.98 ± 4.60	5.90 ± 4.28
Ay (°)	-10.5 ± 46.3 ** ++	-16.3 ± 47.2	-15.0 ± 45.2

* $p<0.05$, ** $p<0.01$ significantly greater or less than neutral.
\+ $p<0.05$, ++ $p<0.01$ significantly greater or less than flexion.

Table 7.5 The influence of neck flexion/extension on the centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions, magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), total path length (TL), mediolateral (TLx) and anteroposterior (TLy) path lengths, mean velocity of sway (Vm), mediolateral (Vxm) and anteroposterior (Vym) sway velocities, and angle of sway from the sagittal plane (Ay) (mean ± SD).

Interaction between sex and vision

The analyses of variance showed a significant interaction between sex and vision for TL, TLx, TLy, Vm, Vxm and Vym. As shown in Table 7.6 with eyes open there was no significant difference in TL, TLx, TLy or Vm, Vxm Vym between females and males. However, without visual feedback males show a significant ($p<0.01$) increase in TL, TLx and TLy, as well as Vm, Vxm and Vym, compared with females.

Postural sway parameter	Eyes open		Eyes closed	
	Females	Males	Females	Males
TL (mm)	166.7 ± 121.2	181.0 ± 135.4	190.9 ± 92.6	244.1 ± 153.4 **
TLx (mm)	94.8 ± 76.0	104.5 ± 84.8	110.9 ± 49.2	144.3 ± 91.8 **
TLy (mm)	100.5 ± 80.0	111.9 ± 87.8	115.2 ± 69.0	152.9 ± 103.3 **
Vm (mm/s)	8.37 ± 6.08	9.08 ± 6.80	9.58 ± 4.64	12.25 ± 7.70 **
Vxm (mm/s)	4.75 ± 3.82	5.27 ± 4.22	5.56 ± 2.47	7.24 ± 4.60 **
Vym (mm/s)	5.04 ± 4.01	5.61 ± 4.40	5.78 ± 3.46	7.67 ± 5.18 **

** significantly ($p<0.01$) greater than female value with eyes closed.

Table 7.6 **The interaction between sex and vision on the total path length (TL), path length in the mediolateral (TLx) and anteroposterior (TLy) directions, mean velocity of sway (Vm) and mean sway velocity in the mediolateral (Vxm) and anteroposterior (Vym) directions (mean ± SD).**

Interaction between sex and sound

The analyses of variance showed a significant interaction between sex and sound for TL, TLx, Vm and Vxm. As shown in Table 7.7 there was no difference in TL and TLx or Vm and Vxm between females and males at 1595Hz. However, at 2916Hz males showed a significant ($p<0.01$) increase in TL and Vm compared with females: this difference was due to the increase in TLx and Vxm in males not observed in females.

Postural sway parameter	Frequency 1595 Hz		Frequency 2916 Hz	
	Females	Males	Females	Males
TL (mm)	181.2 ± 120.9	192.2 ± 138.8	176.4 ± 94.5	232.8 ± 154.3 **
TLx (mm)	104.0 ± 73.9	113.7 ± 88.5	101.6 ± 53.6	135.2 ± 91.3 **
Vm (mm/s)	9.09 ± 6.07	9.65 ± 6.96	8.85 ± 4.74	11.70 ± 7.74 **
Vxm (mm/s)	5.22 ± 3.71	5.70 ± 4.44	5.10 ± 2.69	6.81 ± 4.54 **

** significantly ($p<0.01$) greater than female value with frequency at 2916Hz

Table 7.7 **The interaction between sex and sound on the total path length (TL), path length in the mediolateral (TLx) direction, mean velocity of sway (Vm) and mean sway velocity in the mediolateral (Vxm) direction (mean ± SD).**

Interaction between vision and neck rotation

There were significant interactions between vision and neck rotation for Y and Ay only. As shown in Table 7.8 with eyes open there was a significant ($p<0.01$) posterior shift of the COG projection with neck rotation to the left than when looking directly ahead or rotation to the right. In contrast without visual feedback there was no difference in Y irrespective of neck rotation.

There was significant ($p<0.01$) change of Ay with the neck rotated to the right compared to when looking directly ahead or rotated to the left with visual feedback. In contrast, there was no difference in Ay without visual feedback.

Eyes open

Postural sway parameter	Neck rotation		
	Left	Looking ahead	Right
Y (mm)	-0.03 ± 1.89 **	0.07 ± 2.07	0.18 ± 2.07
Ay (°)	-18.3 ± 47.6	-18.8 ± 49.8	-10.9 ± 52.4 ++

** significantly ($p<0.01$) less than looking directly ahead and rotation to the right.
++ significantly ($p<0.01$) less than looking directly ahead and rotation to the left.

Eyes closed

Postural sway parameter	Neck rotation		
	Left	Looking ahead	Right
Y (mm)	0.13 ± 1.85	0.08 ± 2.01	0.03 ± 1.93
Ay (°)	-9.83 ± 40.9	-13.8 ± 41.5	-11.8 ± 44.0

Table 7.8 **The interaction between vision and neck rotation on the centre of gravity projection in the anteroposterior direction (Y) and angle of sway from the sagittal plane (Ay) (mean ± SD).**

Interaction between vision and neck flexion/extension

Significant interactions between vision and neck flexion/extension were observed for Sx, Sr, Sl, Sy, Sa, Sp, as well as for Ay. As shown in Table 7.9 a significant ($p<0.01$) increase in Sx was observed with neck extension and flexion compared with neutral with the eyes open. Similar increases were also observed for Sr ($p<0.01$) and Sl. However, with eyes closed there was only a significant increase in Sx with neck extension compared with neutral, due to the significant ($p<0.01$) increase in Sr with extension compared with neutral. There also was a significant ($p<0.01$) increase in Sx with extension compared with flexion. A significant increase in Sr and Sl ($p<0.01$) with extension compared with flexion was also observed.

Eyes open

Postural sway parameter	Neck flexion/extension		
	Extension	**Neutral**	**Flexion**
Sx (mm)	1.17 ± 0.61 **	1.10 ± 0.56	1.23 ± 0.52 **
Sr (mm)	0.59 ± 0.37 **	0.56 ± 0.35	0.61 ± 0.28 **
Sl (mm)	0.57 ± 0.27 *	0.54 ± 0.24	0.61 ± 0.28 **
Sy (mm)	0.92 ± 0.39	0.88 ± 0.37	0.95 ± 0.35 **
Sa (mm)	0.45 ± 0.19	0.43 ± 0.18	0.48 ± 0.19 **
Sp (mm)	0.47 ± 0.22	0.45 ± 0.21	0.47 ± 0.18

* p<0.05, ** p<0.01 significantly greater than neutral.

Eyes closed

Postural sway parameter	Neck flexion/extension		
	Extension	**Neutral**	**Flexion**
Sx (mm)	1.70 ± 0.71 * ++	1.55 ± 0.67	1.53 ± 0.62
Sr (mm)	0.85 ± 0.37 ** +	0.77 ± 0.33	0.77 ± 0.35
Sl (mm)	0.85 ± 0.37 ++	0.78 ± 0.39	0.76 ± 0.31
Sy (mm)	1.36 ± 0.56 ** ++	1.23 ± 0.47	1.20 ± 0.49
Sa (mm)	0.68 ± 0.30 ** ++	0.61 ± 0.26	0.61 ± 0.30
Sp (mm)	0.69 ± 0.28 ** ++	0.62 ± 0.24	0.60 ± 0.23

* p<0.05, ** p<0.01 significantly greater than neutral.

+ p<0.05, ++ p<0.01 significantly greater than flexion.

Table 7.9 The interaction between vision and neck flexion/extension on the magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)) (mean ± SD).

Table 7.9 also shows the results for the mean magnitude of anteroposterior sway, showing a significant ($p<0.01$) increase in Sy with flexion compared with neutral with eyes open, due to the significant ($p<0.01$) increase in Sa with flexion compared with neutral. In contrast, with eyes closed there was a significant (p<0.01) increase in Sy, Sa and Sp with neck extension compare with neutral or flexion.

As shown in Table 7.10 there was no change in Ay with visual feedback, but without visual feedback Ay was significantly (p<0.01) reduced when the neck was extended compared with neutral or flexed.

Postural sway parameter	Vision	Neck flexion/extension		
		Extension	Neutral	Flexion
Ay (^{0})	**Eyes open**	-14.9 ± 49.9	-17.8 ± 51.9	-15.3 ± 48.4
	Eyes closed	-6.02 ± 42.0 **	-14.8 ± 42.2	-14.7 ± 41.9

** significantly (p<0.01) less than neutral and flexion with eyes closed.

Table 7.10 The interaction between vision and neck flexion/extension on the angle of sway from the sagittal plane (Ay) (mean ± SD).

Interaction between sex, vision and neck flexion/extension

The analyses of variance showed a significant interaction between sex, vision and neck flexion/extension but only for sway to the left. As shown in Table 7.11 with eyes open in males there was a significant (p<0.01) increase in Sl with neck flexion compared with the neutral or extension. There was no difference in Sl with eyes closed in females or males.

Eyes open

Postural sway parameter	Sex	Neck flexion/extension		
		Extension	Neutral	Flexion
Sl (mm)	**Females**	0.58 ± 0.26	0.55 ± 0.22	0.58 ± 0.21
	Males	0.57 ± 0.27	0.54 ± 0.25	0.65 ± 0.34 **

** significantly (p<0.01) greater than neutral and extension.

Eyes closed

Postural sway parameter	Sex	Neck flexion/extension		
		Extension	Neutral	Flexion
Sl (mm)	**Females**	0.78 ± 0.27	0.72 ± 0.21	0.72 ± 0.23
	Males	0.92 ± 0.43	0.84 ± 0.51	0.79 ± 0.38

Table 7.11 The interaction between sex, vision and neck flexion/extension on the magnitude of sway to the left (Sl) (mean ± SD).

Interaction between neck rotation and neck flexion/extension

The analyses of variance showed a significant interaction between neck rotation and neck flexion/extension for X and Sr only. As shown in Table 7.12 with rotation to the left the COG projection was significantly shifted to the right with neck extension compared with neutral ($p<0.01$) or flexion.

With rotation to the left there was a significant increase in Sr with neck extension compared with neutral, but no difference when compared with flexion. In addition, with rotation to the right there was a significant increase in Sr with neck extension compared with neutral or flexion.

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
X (mm)	Left	3.23 ± 2.52 ** +	3.11 ± 2.47	3.12 ± 2.50
	Looking ahead	3.36 ± 2.51	3.32 ± 2.55	3.26 ± 2.51
	Right	3.36 ± 2.43	3.53 ± 2.59	3.48 ± 2.61
Sr (mm)	Left	0.70 ± 0.32 *	0.66 ± 0.28	0.68 ± 0.28
	Looking ahead	0.68 ± 0.35	0.66 ± 0.40	0.69 ± 0.32
	Right	0.78 ± 0.48 * +	0.67 ± 0.38	0.70 ± 0.36

* $p<0.05$, ** $p<0.01$ significantly greater than neutral.
\+ significantly ($p<0.05$) greater than flexion.

Table 7.12 The interaction between neck rotation and neck flexion/extension on the mediolateral centre of gravity projection (X) and magnitude of sway to the right (Sr) (mean ± SD).

Interaction between sex, neck rotation and neck flexion/extension

An interaction between sex, neck rotation and neck flexion/extension was observed for Ay only. As shown in Table 7.13 in females with rotation to the left there was a significant decrease in Ay with neck extension compared with neutral ($p<0.01$) or flexion. When looking directly ahead Ay was significantly decreased with neck extension ($p<0.01$) or flexion compared with neutral. No differences were observed with rotation to the right. For males when looking directly ahead there was a significant ($p<0.01$) decrease in Ay with neck extension compared with neutral or flexion.

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
Females	Left	-6.01 ± 49.0 ** +	-11.2 ± 47.5	-12.7 ± 44.6
Ay (^{0})	Looking ahead	-9.35 ± 49.5 **	-17.8 ± 48.4	-10.2 ± 48.5 *
	Right	5.11 ± 53.3	-5.64 ± 52.3	-7.19 ± 49.9
Males	Left	-16.7 ± 40.1	-19.2 ± 42.2	-18.6 ± 43.6
Ay (^{0})	Looking ahead	-14.0 ± 43.0 ** ++	-24.2 ± 44.7	-22.5 ± 39.8
	Right	-21.8 ± 37.6	-19.8 ± 47.3	-18.8 ± 44.0

* $p<0.05$, ** $p<0.01$ significantly less than neutral.
+ $p<0.05$, ++ $p<0.01$ significantly less than flexion.

Table 7.13 The interaction between sex, neck rotation and neck flexion/extension on the angle of sway from the sagittal plane (Ay) (mean ± SD).

Interaction between vision, sound and neck rotation

A significant interaction between vision, sound and neck rotation was observed for Sp only. Table 7.14 shows that with visual feedback and a frequency of 1595Hz there were no differences in Sp, in contrast at 2916Hz there was significant reduction in Sp with rotation to the right or left compared with looking directly ahead. Without vision no differences were observed.

Interaction between sex, sound, neck rotation and neck flexion/extension

Only Sx showed a significant interaction between sex, sound, neck rotation and neck flexion/extension. As shown in Table 7.15 at 1595Hz with rotation to the left or looking directly ahead there was no difference in Sx between neutral, neck flexion or extension in either females or males. However, with rotation to the right there was a significant increase in Sx with neck extension ($p<0.01$) and flexion compared with neutral in females, while in males there was a significant ($p<0.01$) increase in Sx with neck extension compared with neutral or flexion.

Eyes open

Postural sway parameter	Frequency	Neck rotation		
		Left	Looking ahead	Right
Sp (mm)	**1595 Hz**	0.45 ± 0.15	0.44 ± 0.16	0.48 ± 0.29
	2916 Hz	0.46 ± 0.16 *	0.50 ± 0.23	0.45 ± 0.19 *

* significantly ($p<0.05$) less than looking directly ahead.

Eyes closed

Postural sway parameter	Frequency	Neck rotation		
		Left	Looking ahead	Right
Sp (mm)	**1595 Hz**	0.61 ± 0.20	0.62 ± 0.23	0.61 ± 0.23
	2916 Hz	0.67 ± 0.29	0.63 ± 0.25	0.67 ± 0.30

Table 7.14 The interaction between vision, sound and neck rotation on the magnitude of posterior sway (Sp) (mean ± SD).

Frequency 1595 Hz

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
Females	Left	1.29 ± 0.44	1.25 ± 0.41	1.34 ± 0.39
Sx (mm)	Looking ahead	1.26 ± 0.43	1.28 ± 0.42	1.26 ± 0.41
	Right	1.48 ± 0.64 **	1.19 ± 0.48	1.35 ± 0.49 *
Males	Left	1.35 ± 0.73	1.23 ± 0.49	1.29 ± 0.60
Sx (mm)	Looking ahead	1.29 ± 0.69	1.20 ± 0.64	1.31 ± 0.61
	Right	1.52 ± 0.88 ** ++	1.32 ± 0.72	1.30 ± 0.60

* $p<0.05$, ** $p<0.01$ significantly greater than neutral.
++ significantly ($p<0.01$) greater than flexion.

Frequency 2916 Hz

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
Females	Left	1.39 ± 0.53	1.32 ± 0.50	1.37 ± 0.51
Sx (mm)	Looking ahead	1.30 ± 0.49 *	1.20 ± 0.49	1.35 ± 0.57 *
	Right	1.58 ± 1.02	1.36 ± 0.66	1.35 ± 0.53
Males	Left	1.59 ± 0.79 * +	1.43 ± 0.63	1.39 ± 0.63
Sx (mm)	Looking ahead	1.61 ± 0.91	1.55 ± 1.05	1.58 ± 0.78
	Right	1.53 ± 0.74	1.55 ± 1.00	1.62 ± 0.79

* significantly ($p<0.05$) greater than neutral.
+ significantly ($p<0.05$) greater than flexion.

Table 7.15 The interaction between sex, sound, neck rotation and neck flexion/extension on the magnitude of mediolateral sway (Sx) (mean ± SD).

At 2916Hz with rotation to the left there were no significant differences in Sx with neck flexion/extension in females. In contrast, in males there was a significant increase in Sx with neck extension compared with neutral or flexion. When looking directly ahead females showed a significant increase in Sx with neck extension and flexion compared with neutral. No differences were observed in males when looking directly ahead. With rotation to the right there was no difference in Sx for either females or males (Table 7.15).

Interaction between vision, sound, neck rotation and neck flexion/extension

Only Ay showed a significant interaction between vision, sound, neck rotation and neck flexion/extension. As shown in Table 7.16 at 1595Hz when looking directly ahead with eyes open there was a significant reduction in Ay with neck extension compared with neutral, but not with flexion. In contrast, there was no difference in Ay with any neck flexion/extension with rotation to the right or left. With the eyes closed rotation to the left significantly ($p<0.01$) decreased Ay with neck extension compared with neutral or flexion. When looking directly ahead there was a significant ($p<0.01$) reduction in Ay with neck extension compared with neutral, but not flexion.

Table 7.16 also shows the results at 2916Hz. No differences were observed with the eyes open. However, with eyes closed and rotation to the left a significant decrease in Ay with neck extension was observed compared with neutral, but not with flexion. When looking directly ahead or rotation to the right there was a significant reduction in Ay with neck extension compared with neutral and flexion.

Interaction between sex, vision, sound, neck rotation and neck flexion/extension

There was only a significant interaction between sex, vision, sound, neck rotation and neck flexion/extension for TLx. As shown in Table 7.17 females with eyes open at 1595Hz with neck rotation to the left showed a significant increase in TLx with neck extension or flexion compared with neutral. However, no differences in any neck flexion/extension when looking directly ahead or with rotation to the right were observed. With eyes closed at 1595Hz there were no differences for any neck flexion/extension when looking directly ahead or with rotation to the left. With rotation to the right there was a significant increase in TLx with neck extension and flexion compared with neutral.

For males standing with eyes open at 1595Hz there were no differences in any neck flexion/extension condition when looking directly ahead or with rotation to the right or left. In contrast, with eyes closed there was a significant increase in TLx with neck extension compared with flexion, but not with neutral when the neck was rotated to the right or left ($p<0.01$). No differences were observed when looking directly ahead (Table 7.17).

Frequency 1595 Hz

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
Eyes open	**Left**	-22.0 ± 52.9	-23.8 ± 53.8	-16.8 ± 51.3
Ay (^{0})	**Looking ahead**	-14.9 ± 55.3 **	-23.3 ± 55.2	-22.0 ± 51.7
	Right	-6.41 ± 54.8	-7.95 ± 61.0	-8.46 ± 57.0
Eyes closed	**Left**	-5.28 ± 43.3 ** ++	-16.8 ± 42.8	-19.5 ± 43.9
Ay (^{0})	**Looking ahead**	-9.26 ± 46.4 **	-24.4 ± 40.6	-17.1 ± 41.8
	Right	-11.4 ± 47.0	-14.1 ± 49.2	-18.8 ± 49.9

** significantly ($p<0.01$) less than neutral.
++ significantly ($p<0.01$) less than flexion.

Frequency 2916 Hz

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
Eyes open	**Left**	-16.1 ± 44.2	-12.5 ± 43.6	-18.6 ± 41.6
Ay (^{0})	**Looking ahead**	-17.8 ± 43.5	-21.6 ± 48.5	-13.4 ± 46.8
	Right	-12.3 ± 50.3	-17.7 ± 49.8	-12.6 ± 43.4
Eyes closed	**Left**	-2.09 ± 37.1 *	-7.66 ± 38.9	-7.70 ± 39.8
Ay (^{0})	**Looking ahead**	-4.81 ± 39.7 * +	-14.6 ± 42.1	-12.9 ± 38.7
	Right	-3.26 ± 40.2 * +	-11.1 ± 40.6	-12.1 ± 38.2

* significantly ($p<0.05$) less than neutral.
+ significantly ($p<0.05$) less than flexion.

Table 7.16 The interaction between vision, sound, neck rotation and neck flexion/extension on the angle of sway from the sagittal plane (Ay) (mean ± SD).

Frequency 1595 Hz

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
Eyes open				
Females	**Left**	88.8 ± 31.0 *	73.6 ± 19.9	85.0 ± 23.3 *
TLx (mm)	**Looking ahead**	84.4 ± 38.6	94.4 ± 66.7	90.0 ± 42.3
	Right	117.5 ± 110.6	132.7 ± 217.0	93.2 ± 49.0
Males	**Left**	94.2 ± 62.2	85.7 ± 39.9	95.3 ± 45.7
TLx (mm)	**Looking ahead**	86.7 ± 38.9	81.4 ± 37.2	87.6 ± 38.9
	Right	139.9 ± 206.9	129.8 ± 168.7	114.0 ± 117.6
Eyes closed				
Females	**Left**	107.6 ± 37.3	103.3 ± 25.7	110.1 ± 49.3
TLx (mm)	**Looking ahead**	113.5 ± 67.7	102.6 ± 32.4	107.6 ± 56.0
	Right	133.6 ± 60.2 *	111.1 ± 68.7	123.4 ± 82.8 *
Males	**Left**	137.4 ± 66.1 ++	114.0 ± 40.5	109.1 ± 55.4
TLx (mm)	**Looking ahead**	119.3 ± 65.5	116.1 ± 65.7	116.0 ± 53.5
	Right	162.6 ± 91.0 ++	138.5 ± 105.5	118.3 ± 65.9

* significantly ($p<0.05$) greater than neutral.
++ significantly ($p<0.01$) greater than flexion.

Frequency 2916 Hz

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
Eyes open				
Females	**Left**	91.7 ± 52.4	88.3 ± 51.6	96.2 ± 53.4
TLx (mm)	**Looking ahead**	88.3 ± 37.8	82.3 ± 45.8	90.8 ± 57.0
	Right	115.9 ± 107.3	98.7 ± 84.3	93.9 ± 49.9
Males	**Left**	106.2 ± 51.8	94.0 ± 66.4	112.1 ± 67.2
TLx (mm)	**Looking ahead**	110.0 ± 54.7	117.7 ± 111.0	114.9 ± 58.3
	Right	102.0 ± 36.7	104.0 ± 56.3	105.4 ± 42.1
Eyes closed				
Females	**Left**	113.2 ± 40.2	106.2 ± 34.0	111.5 ± 45.5
TLx (mm)	**Looking ahead**	105.9 ± 36.0	103.0 ± 46.4	105.7 ± 44.7
	Right	125.9 ± 51.8 **	107.8 ± 41.4	103.6 ± 45.2
Males	**Left**	172.3 ± 97.3 **	158.4 ± 75.9 *	135.4 ± 62.8
TLx (mm)	**Looking ahead**	183.2 ± 148.1	162.1 ± 107.1	137.9 ± 66.8
	Right	169.7 ± 74.2	161.4 ± 82.5	186.0 ± 190.3

* $p<0.05$, ** $p<0.01$ significantly greater than flexion.

Table 7.17 **The interaction between sex, vision, sound, neck rotation and neck flexion/extension on the path length in the mediolateral direction (TLx) (mean ± SD).**

As shown in Table 7.17 for females with eyes open at 2916Hz no differences were observed in any neck flexion/extension when looking directly ahead or with rotation to the right or left. With eyes closed there were no differences in any neck flexion/extension when looking directly ahead or rotation to the left, however with rotation to the right there was a significant ($p<0.01$) increase in TLx with neck extension compared with flexion, but not neutral.

For the males with eyes open at 2916Hz there were again no differences in any neck flexion/extension when looking directly ahead or with rotation to the right or left. However, with eyes closed with rotation to the left there was a significant ($p<0.01$) increase in TLx with neck extension compared with flexion, but not neutral. There also was a significant increase in TLx with neutral compared with neck flexion.

7.4 Discussion

By placing marker on a screen as in Experiment 1 (Chapter 4) the nature of this experiment corresponds to that earlier. As previously, the differences between the sexes would not be expected to produce angular changes in either rotation or flexion/extension of the neck.

As expected and in common with other studies (Day et al. 1993; Kollegger et al. 1992; Toupet at al. 1992) visual feedback had a stabilising effect on postural sway behaviour. Although vision had no influence on the mean COG projection in the anteroposterior direction or the angle of sway from the sagittal plane, in combination with neck rotation it influences both parameters. It might be speculated that if visual feedback alone has no influence on the anteroposterior COG projection and the angle of sway, vision combines with neck proprioceptive input in order to control the mean anteroposterior COG and the angle of sway from the sagittal plane.

As with other studies (Juntunen et al. 1987; Raper and Soames 1991; Kilburn et al. 1992; Soames and Raper 1992), sound was observed to influence balance and sway behaviour. Although the frequency of the sound does not appear to influence the magnitude of sway in the anteroposterior direction as observed by Sakellari and Soames (1996), it does influence mediolateral sway magnitude. Nevertheless, the findings confirm the observation of Sakellari and Soames (1996) that the frequency of 1595Hz has a more stabilising effect on postural maintenance than that of 2916Hz. It is, therefore confirmed that the magnitude of sway can be modified by the auditory system depending on the frequency of sound.

Rotation of the neck influences the COG projection, the total path length and the mean velocity of sway in the mediolateral direction. In addition to the findings of Lund (1980) and Smetanin et al. (1993), the observations in this experiment indicate that neck proprioceptive input has an influence in the mediolateral direction. Since the majority of the population is right-handed the influence of neck rotation appears to be dominant when rotation is to the right. The difference between neck rotation to the right and left is an area for further investigation.

Neck flexion/extension, as expected from Experiment 1, influenced postural balance, with extension causing a decrease in postural stability but flexion having little effect. With the neck extended the vestibular system is depolarised, whereas when flexed it is hyperpolarised (Livingston, 1990; Sherwood 1997). The decrease in postural stability induced by neck extension is due to the otoliths not being situated within their working range (Brandt et al. 1981). However, with practice postural stability can be improved with neck extension suggesting moderation of the vestibulospinal mechanism (Brandt et al. 1981). Thus, it is seen that neck extension has a greater effect on the vestibular system than does flexion leading immediately to postural instability. Neck extension also causes a reduction in the angle of sway from the sagittal plane, a finding not observed in Chapter 4. It is suggested that this is the result of the vestibular input.

The interaction between vision and neck rotation influences the mean anteroposterior COG projection and the angle of sway. There is, however a different effect with rotation to the right compared with rotation to the left. However, the interaction between vision and neck rotation appears to have a more stabilising effect with rotation to the right on the basis of these findings. This may be due to the majority of the population being right-handed, but requires further investigation.

The interaction between vision and neck flexion/extension influences the magnitude of sway in both the mediolateral and anteroposterior directions, as well as the angle of sway from the sagittal plane. This interaction leads to an increase in the magnitude of mediolateral sway. It is possible that the influence of the visual and vestibular system is additive in the mediolateral direction since with the feet together both the visual and vestibular systems are sensitised to detect lateral body motion (Day et al. 1993). In controlling anteroposterior sway the vestibular input associated with neck flexion seems to be more effective than vision: in contrast, vision is more powerful than the vestibular input associated with neck extension. Similarly, vision is more powerful than the vestibular input from neck extension in determining the angle of sway from the sagittal plane. The findings in this experiment confirm the observations of Zacharias and Young (1981) that the interaction between vision and the vestibular system is dependent on the degree of agreement between the visual and vestibular inputs. In addition, it is suggested that for the anteroposterior direction the agreement depends on the vestibular system when its input is associated with neck flexion, but relies upon vision when the vestibular input is associated with neck extension.

The interaction between vision, sound and neck rotation decreases the magnitude of posterior sway, being more apparent when the sound has a destabilising effect on posture. Although in this experiment there is no interaction between vision and the auditory system, such an interaction has been reported to increase sway behaviour (Sakellari and Soames 1996). It is possible that neck rotation may attenuate the conflict between vision and sound resulting in postural stability, particularly posteriorly.

The interaction between vision, sound, neck rotation and neck flexion/extension on the angle of sway from the sagittal plane was observed under both the stabilising and destabilising effect of sound. Without visual feedback the angle of sway was reduced, while with visual feedback there were no differences. It is, therefore suggested that the interaction between visual, vestibular, neck proprioceptive and auditory inputs stabilise posture by controlling the angle of sway.

The interaction between neck rotation and neck flexion/extension decreases postural stability and moves the mean COG projection to the right. This may be due to the majority of the population being right-handed and it is, therefore easier to protect themselves if a fall occurs. The effect of the interaction between neck rotation and neck flexion/extension in this experiment does not show the same influence in the anteroposterior direction as observed in the Chapter 4. It is suggested that in the mediolateral direction the interaction between vestibular and neck proprioceptor input influences the mean mediolateral COG projection. The effect of the interaction is additive and confirms the findings of both Anatasopoulos and Mergner (1982) and Karnath et al. (1994).

Although gender had no effect on postural sway behaviour as such, there were interactions between sex and the other main variables (vision, sound, neck rotation and neck flexion/extension). The interaction between sex and vision showed that vision influenced both sexes in controlling the total path length and velocity of sway in the mediolateral and anteroposterior directions, but that it had a more stabilising effect in males than it did in females, since males show a greater total path length and velocity of sway than females when there is no visual feedback. This observation confirms the finding of Kollegger et al. (1992).

The interaction between sex and sound was observed to influence the control of mediolateral, but not anteroposterior, sway. In the current experiment the results show that sound appears to have greater influence on path length and the velocity of sway in males than in females. It is suggested that the auditory system in males is more sensitive to the frequency of sound than it is in females for postural maintenance.

The interaction between sex, vision and neck flexion/extension revealed that the magnitude of sway to the left was greater in males when the neck is flexed with visual feedback. It is suggested that the vestibular input from neck flexion has a stronger effect in males in this combination, with vision being the primary controlling factor for mediolateral sway.

The interaction between sex, neck rotation and neck flexion/extension appears to influence stability in females, but only for the angle of sway from the sagittal plane. It has been suggested that females have greater difficulty in postural control because of their physique (Berger et al. 1992), since input from neck proprioception and the vestibular system perceives trunk motion (Mergner et al. 1991), as well as the results of this experiment that vision is more important in males than females. It is, therefore possible that the interaction between neck proprioceptor and vestibular input has a more powerful effect in females than males in monitoring postural deviations to improve balance.

Under conditions of the interaction between sex, sound, neck rotation and neck flexion/extension an increase in the magnitude of mediolateral sway was observed in both sexes. In females the interaction appears to be dependent on vestibular input during both neck extension and flexion, while in males it seems to rely upon input from neck extension only. The frequency of sound also appears to be important in males in the interaction between vestibular, neck proprioceptive and auditory system.

The interaction between sex, vision, sound, neck rotation and neck flexion/extension was observed to influence the path length in the mediolateral direction only. The stabilising effect of sound appears to be important in males since in females there was an increase in mediolateral path length when neck rotation was to the left, while the destabilising effect of sound appears to influence in both sexes. It is suggested that the vision, auditory, neck proprioception and vestibular inputs interact with each other to stabilise the body by controlling the path length in the mediolateral direction.

7.5 Summary

The response of static visual, auditory, vestibular and neck proprioceptor input all influence postural maintenance. Visual input is the major stabilising factor, whereas the vestibular and neck proprioceptor systems have a destabilising effect with the effect of auditory input being frequency dependent. The visual-neck proprioceptor interaction and visual-auditory-neck proprioceptor interaction leads to the stabilisation of anteroposterior sway. In contrast, the interaction between visual-vestibular inputs and the neck proprioceptor-vestibular interaction causes destabilisation, mainly in the mediolateral direction. The visual-vestibular-neck proprioceptor-auditory interaction influences the angle of sway from the sagittal plane. Vision and the auditory system appear to be important in males in postural maintenance, while the interaction between neck proprioceptor and vestibular inputs is important in females in controlling sway direction. There is an interaction between vision, sound, vestibular and neck proprioception which is important in both sexes in controlling the path length in the mediolateral direction.

Chapter 8
Experiment 4: Responses to dynamic vestibular, neck proprioceptor with auditory stimulation while visually tracking a moving target

8.1 Introduction

Postural control usually requires sensory inputs from the visual, vestibular and/or proprioceptor systems. Auditory information, another input, has been shown to play a role in postural maintenance (Juntunen et al. 1987; Raper and Soames 1991; Kilburn et al. 1992; Soames and Raper 1992; Sakellari and Soames 1996). Receptors associated with all four systems are situated in the head, a part of body that is freely mobile. The head is, therefore clearly important in postural balance (Pozzo et al. 1990). Thus, the objective of this experiment is to investigate the influence of the individual sensory inputs and combinations of vestibular, neck proprioceptor and auditory input while tracking a moving target on postural sway behaviour.

8.2 Materials and methods

Thirty healthy subjects (15 females, 15 males), aged between 18 and 30 years, agreed to participate in the experiment. The subjects were the same as those who participated in Experiment 3 (Chapter 7).

When visually tracking a moving target by moving the head there were a total 32 combinations of conditions for each subject: horizontal head movement with the neck in neutral (N), extended (E) or flexed (F) 45^0, vertical head movement while looking directly ahead (A), or with the neck rotated to the right (R) or left (L) 45^0, diagonal head movement from 45^0 rotation to the right and extended (RE) or 45^0 rotation to the left and extended (LE), at each of two velocities of head movement (0.2m/s and 1.0m/s) each with auditory stimulation of

1595Hz and 2916Hz. The postural sway recordings were all taken with the subject standing comfortably erect with the feet together and wearing goggles to restrict the field of view to enhance tracking by moving the head (for further details see Chapter 3 part 3.7.4).

Four-way analyses of variance were conducted for each sway parameter (Chapter 3 part 3.3) with sex, sound, velocity and direction of head movement as independent variables in order to determine the influence of each on postural sway behaviour. t-tests were conducted as appropriate to determine significant differences for each independent variable. Unless otherwise stated all differences are at the 5% level of significance.

8.3 Results

8.3.1 Subject characteristics

Because the population studied in this experiment is the same as for experiment 3 (Chapter 7), the characteristics are as given in Table 7.1 (Page 96).

8.3.2 Analyses of variance

The analyses of variance showed significant sex, velocity of head movement and direction of head movement influences, as well as interactions between these variables on postural sway behaviour. In addition, an interaction between sound and the velocity of head movement, and sound and the direction of head movement were also observed (Appendix 9).

Sex

Few differences in sway behaviour was observed between females and males, the difference being restricted to X. The COG projection for females being significantly ($p<0.01$) shifted to the right (4.01 ± 2.26) compared with males (1.89 ± 1.93).

Velocity of head movement

The velocity of head movement influenced most postural sway parameters. As shown in Table 8.1 the higher velocity significantly ($p<0.01$) increased Sx, including Sr and Sl separately, and Sy, including Sa and Sp separately. In addition TL and Vm, as well as their separate components were all significantly ($p<0.01$) increased at the higher velocity. No differences were observed for X, Y and Ay.

Postural sway parameter	Velocity of head movement	
	0.2 m/s	1.0 m/s
X (mm)	2.97 ± 2.36	2.94 ± 2.35
Y (mm)	-0.16 ± 1.87	-0.12 ± 1.85
Sx (mm)	1.59 ± 0.60	1.76 ± 0.65 **
Sr (mm)	0.80 ± 0.31	0.87 ± 0.34 **
Sl (mm)	0.79 ± 0.30	0.88 ± 0.33 **
Sy (mm)	1.34 ± 0.52	1.64 ± 0.62 **
Sa (mm)	0.67 ± 0.26	0.82 ± 0.31 **
Sp (mm)	0.67 ± 0.28	0.81 ± 0.35 **
TL (mm)	218.3 ± 112.3	242.3 ± 110.3 **
TLx (mm)	128.2 ± 66.4	139.9 ± 64.9 **
TLy (mm)	135.0 ± 79.9	154.0 ± 81.3 **
Vm (mm/sec)	11.0 ± 5.64	12.2 ± 5.53 **
Vxm (mm/sec)	6.43 ± 3.33	7.02 ± 3.26 **
Vym (mm/sec)	6.77 ± 4.01	7.73 ± 4.08 **
Ay (°)	-14.8 ± 37.0	-13.1 ± 32.6

** significantly ($p<0.01$) greater than lower velocity.

Table 8.1 The influence of the velocity of head movement on the centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions, magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), total path length (TL), mediolateral (TLx) and anteroposterior (TLy) path lengths, mean velocity of sway (Vm), mediolateral (Vxm) and anteroposterior (Vym) sway velocities, and angle of sway from the sagittal plane (Ay) (mean ± SD).

Direction of head movement

The direction of head movement was observed to influence most postural sway parameters, except X and Ay. As shown in Table 8.2 the only significant difference in Y was for horizontal head movement with neck flexion, which resulted in a shift in the COG projection posteriorly compared with neutral. There was no difference for any neck position for vertical and diagonal head movements. No differences were observed for diagonal head movement compared with horizontal or vertical movement.

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
Y (mm)	-0.12 ± 1.83	0.01 ± 1.89	-0.18 ± 1.90 *

* significantly ($p<0.05$) less than neutral.

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
Y (mm)	-0.08 ± 1.83	-0.22 ± 1.76	-0.14 ± 1.88

Postural sway parameter	Diagonal head movement	
	LE	RE
Y (mm)	-0.15 ± 1.95	-0.23 ± 1.88

Table 8.2 The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotated to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the anteroposterior centre of gravity projection (Y) (mean ± SD).

As shown in Table 8.3 there was a significant increase in Sx, Sr and Sl for horizontal head movement with neck extension compared with neutral and a significant ($p<0.01$) increase compared with flexion. For vertical movements there was a significant increase in Sx with rotation to the left compared with looking directly ahead; this was due to an increase in Sr. There was no difference in Sl when looking directly ahead compared with rotation to the right or left. No differences in Sx, Sr and Sl were observed for diagonal head movement. There was a significant ($p<0.01$) increase in Sx, due to the increase in Sr and Sl ($p<0.01$), for

LE diagonal head movement compared with horizontal head movement with neck flexion.

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
Sx (mm)	1.80 ± 0.84 * ++	1.60 ± 0.70	1.59 ± 0.57
Sr (mm)	0.90 ± 0.43 * ++	0.79 ± 0.37	0.80 ± 0.30
Sl (mm)	0.90 ± 0.41 * ++	0.80 ± 0.36	0.80 ± 0.29

* significantly ($p<0.05$) greater than neutral.
++ significantly ($p<0.01$) greater than flexion.

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
Sx (mm)	1.69 ± 0.56 *	1.57 ± 0.52	1.68 ± 0.53
Sr (mm)	0.84 ± 0.30 *	0.79 ± 0.28	0.85 ± 0.29
Sl (mm)	0.84 ± 0.28	0.79 ± 0.26	0.83 ± 0.26

* significantly ($p<0.05$) greater than looking directly ahead.

Postural sway parameter	Diagonal head movement	
	LE	RE
Sx (mm)	1.80 ± 0.66 **	1.66 ± 0.54
Sr (mm)	0.89 ± 0.33 *	0.83 ± 0.28
Sl (mm)	0.91 ± 0.35 **	0.83 ± 0.28

* $p<0.05$, ** $p<0.01$ significantly greater than horizontal head movement with flexion.

Table 8.3 The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of mediolateral sway (Sx) (separately to the right (Sr) and left (Sl)) (mean ± SD).

As shown in Table 8.4 there was a significant increase in Sy with horizontal head movement with neck extension compared with neutral, the increase being due to the significant ($p<0.01$) increase in Sa. In addition, there was a significant ($p<0.01$) increase in Sy, Sa and Sp with extension compared with flexion. For vertical movements a significant decrease in Sy was observed with rotation to the right compared with looking directly ahead, again due to a significant decrease in Sa. With rotation to the left there was a significant ($p<0.01$) reduction in Sy, Sa and Sp compared with looking directly ahead. There was no difference for head movement in a diagonal plane. There was a significant ($p<0.01$) increase in Sy, Sa and Sp for LE diagonal head movement compared with horizontal head movement with neck extension. In addition, a significant ($p<0.01$) increase in Sy, Sa and Sp was observed for both diagonal head movements compared with horizontal head movement with neck flexion.

Postural sway parameter	**Horizontal head movement**		
	Extension	**Neutral**	**Flexion**
Sy (mm)	1.42 ± 0.54 * +	1.24 ± 0.63	1.25 ± 0.48
Sa (mm)	0.71 ± 0.27 ** +	0.61 ± 0.24	0.63 ± 0.25
Sp (mm)	0.71 ± 0.29 +	0.63 ± 0.49	0.63 ± 0.25

* $p<0.05$, ** $p<0.01$ significantly greater than neutral.
+ significantly ($p<0.05$) greater than flexion.

Postural sway parameter	**Vertical head movement**		
	Left	**Looking ahead**	**Right**
Sy (mm)	1.52 ± 0.52 **	1.72 ± 0.63	1.58 ± 0.57 *
Sa (mm)	0.77 ± 0.27 **	0.87 ± 0.35	0.79 ± 0.28 *
Sp (mm)	0.75 ± 0.26 **	0.84 ± 0.29	0.79 ± 0.30

* $p<0.05$, ** $p<0.01$ significantly less than looking directly ahead.

Postural sway parameter	**Diagonal head movement**	
	LE *	**RE ***
Sy (mm)	1.66 ± 0.62 +	1.52 ± 0.55
Sa (mm)	0.83 ± 0.32 +	0.76 ± 0.29
Sp (mm)	0.83 ± 0.31 +	0.76 ± 0.28

* significantly ($p<0.01$) greater than horizontal head movement with flexion.
+ significantly ($P<0.01$) greater than horizontal head movement with extension.

Table 8.4 **The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)) (mean ± SD).**

As shown in Table 8.5 there was a significant ($p<0.01$) increase in TL with horizontal head movement with neck extension compared with neutral, being due to the significant ($p<0.01$) increase in TLy. In addition, there was a significant ($p<0.01$) increase in TL, TLx and TLy with neck extension compared with flexion. For vertical movement there was no difference in TL between the various neck postures, however a significant ($p<0.01$) increase in TLx with rotation to the right compared with looking directly ahead was observed. TLy was significantly ($p<0.01$) reduced with rotation to the left compared with looking directly ahead, but not when rotated to the right. No differences were observed for diagonal head movements.

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
TL (mm)	234.6 ± 116.5	212.6 ± 113.9 **	212.4 ± 106.1 **
TLx (mm)	141.1 ± 69.9	130.3 ± 69.7	125.7 ± 61.5 **
TLy (mm)	143.2 ± 83.3	125.4 ± 77.6 **	129.9 ± 77.5 **

** significantly ($p<0.01$) less than extension.

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
TL (mm)	226.6 ± 102.6	236.2 ± 111.7	237.2 ± 112.5
TLx (mm)	131.7 ± 59.5	127.8 ± 67.0	136.6 ± 65.2 **
TLy (mm)	142.5 ± 74.4 **	157.4 ± 80.5	151.0 ± 82.3

** significantly ($p<0.01$) greater or less than looking directly ahead.

Postural sway parameter	Diagonal head movement	
	LE	RE
TL (mm)	247.7 ± 115.2 *	235.3 ± 114.2 *
TLx (mm)	143.5 ± 68.0 *	135.6 ± 65.6 *
TLy (mm)	156.7 ± 82.7 *	149.5 ± 86.3 *

* significantly ($p<0.01$) greater than horizontal head movement with flexion.

Table 8.5 **The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the total path length (TL) and path length in the mediolateral (TLx) and anteroposterior (TLy) directions (mean ± SD).**

There was a significant (p<0.01) increase in TL, TLx and TLy for diagonal head movements compared with horizontal head movement with neck flexion (Table 8.5).

Not surprisingly as shown in Table 8.6 the findings for Vm, Vxm and Vym corresponded with TL, TLx and TLy with respect to the significant differences observed in relation to the direction of head movement.

Postural sway parameter	**Horizontal head movement**		
	Extension	**Neutral**	**Flexion**
Vm (mm/s)	11.8 ± 5.85	10.7 ± 5.72 **	10.7 ± 5.33 **
Vxm (mm/s)	7.08 ± 3.51	6.54 ± 3.50	6.31 ± 3.09 **
Vym (mm/s)	7.18 ± 4.18	6.29 ± 3.90 **	6.52 ± 3.89 **

** significantly (p<0.01) less than extension.

Postural sway parameter	**Vertical head movement**		
	Left	**Looking ahead**	**Right**
Vm (mm/s)	11.4 ± 5.15	11.9 ± 5.61	11.9 ± 5.65
Vxm (mm/s)	6.61 ± 2.99	6.41 ± 3.36	6.85 ± 3.27 **
Vym (mm/s)	7.15 ± 3.73 **	7.90 ± 4.04	7.58 ± 4.13

** significantly (p<0.01) greater or less than looking directly ahead.

Postural sway parameter	**Diagonal head movement**	
	LE	**RE**
Vm (mm/s)	12.4 ± 5.78 *	11.8 ± 5.73 *
Vxm (mm/s)	7.20 ± 3.41 *	6.80 ± 3.29 *
Vym (mm/s)	7.86 ± 4.15 *	7.50 ± 4.33 *

* significantly (p<0.01) greater than horizontal head movement with flexion.

Table 8.6 **The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the mean velocity of sway (Vm) and mean sway velocity in the mediolateral (Vxm) and anteroposterior (Vym) directions (mean ± SD).**

Interaction between sex and the velocity of head movement

The analyses of variance showed a significant interaction between sex and the velocity of head movement for Sp only. Although the initial analysis of variance showed a significant sex-head movement velocity interaction, the differences were between inappropriate comparisons, i.e. male-low velocity compared with females-high velocity.

Interaction between sound and the velocity of head movement

A significant interaction between sound and the velocity of head movement was only observed for Sp. Although the initial analysis of variance showed a significant sound-velocity of head movement interaction, the differences were between inappropriate comparisons, i.e. at 1595Hz with the lower velocity compared with at 2916Hz with the higher velocity.

Interaction between sound and the direction of head movement

The analyses of variance showed a significant interaction between sound and the direction of head movement for all mediolateral postural sway parameters except the COG projection. As shown in Table 8.7 there was a significant increase in Sx at 1595Hz with horizontal head movement with neck extension compared with flexion, due to the increase in both Sr and Sl. At 2916Hz there was a significant increase in Sx with neck extension compared with neutral ($p<0.01$) and flexion, due to the increases in both Sr and Sl. There was also a significant increase in Sx with neck flexion compared with neutral, due to the increase in Sr.

For vertical head movement (Table 8.7) at 1595Hz there was a significant ($p<0.01$) increase in Sx with rotation to the left compared with looking directly ahead due to the significant ($p<0.01$) increase in Sr and Sl. In addition, there was a significant increase in Sx with rotation to the left compared with rotation to the right, due to an increase in Sl. There was also a significant increase in Sr with rotation to the right compared with looking directly ahead. No differences in Sx, Sr and Sl with vertical head movement were observed at 2916Hz.

Postural sway parameter	Frequency	Horizontal head movement		
		Extension	Neutral	Flexion
Sx (mm)	1595 Hz	1.77 ± 0.72 +	1.73 ± 0.79	1.59 ± 0.55
	2916 Hz	1.84 ± 0.94 ** +	1.47 ± 0.59	1.60 ± 0.59 *
Sr (mm)	1595 Hz	0.89 ± 0.37 +	0.86 ± 0.41	0.80 ± 0.31
	2916 Hz	0.92 ± 0.49 ** +	0.72 ± 0.31	0.79 ± 0.29 *
Sl (mm)	1595 Hz	0.88 ± 0.36 +	0.87 ± 0.39	0.79 ± 0.26
	2916 Hz	0.92 ± 0.46 ** +	0.74 ± 0.32	0.80 ± 0.32

* $p<0.05$, $p<0.01$ significantly greater than neutral.
+ significantly ($p<0.05$) greater than flexion.

Postural sway parameter	Frequency	Vertical head movement		
		Left	Looking ahead	Right
Sx (mm)	1595 Hz	1.75 ± 0.57 ** +	1.54 ± 0.50	1.64 ± 0.49
	2916 Hz	1.62 ± 0.56	1.60 ± 0.55	1.72 ± 0.57
Sr (mm)	1595 Hz	0.87 ± 0.29 **	0.76 ± 0.25	0.83 ± 0.28 *
	2916 Hz	0.82 ± 0.30	0.81 ± 0.31	0.86 ± 0.30
Sl (mm)	1595 Hz	0.88 ± 0.29 ** +	0.78 ± 0.27	0.80 ± 0.23
	2916 Hz	0.80 ± 0.28	0.79 ± 0.26	0.86 ± 0.28

* $p<0.05$, ** $p<0.01$ significantly greater than looking directly ahead.
+ significantly ($p<0.05$) greater than rotation to the right.

Postural sway parameter	Frequency	Diagonal head movement	
		LE	RE
Sx (mm)	1595 Hz	1.85 ± 0.69	1.70 ± 0.55
	2916 Hz	1.76 ± 0.63	1.62 ± 0.53
Sr (mm)	1595 Hz	0.91 ± 0.33	0.84 ± 0.29
	2916 Hz	0.87 ± 0.33	0.82 ± 0.28
Sl (mm)	1595 Hz	0.94 ± 0.37	0.85 ± 0.28
	2916 Hz	0.89 ± 0.32	0.80 ± 0.29

Table 8.7 The interaction between sound frequency and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of mediolateral sway (Sx) (separately to the right (Sr) and left (Sl)) (mean ± SD).

No differences in Sx, Sr and Sl were observed at either sound frequency for diagonal head movement (Table 8.7). However, at 1595Hz there was a significant ($p<0.01$) increase in Sx for LE diagonal head movement, due to the increase in both Sr ($p<0.01$) and Sl compared with horizontal head movement with neck flexion. In addition, there was also a significant ($p<0.01$) increase in Sx in LE diagonal head movement, due to the increase in both Sr and Sl ($p<0.01$) compared with vertical movement with rotation to the right. No differences were observed for diagonal head movement compared with horizontal and vertical movement at 2916Hz.

As shown in Table 8.8 with horizontal head movement at 1595Hz a significant ($p<0.01$) increase in TLx was observed with neck extension compared with flexion. However, at 2916Hz there was a significant ($p<0.01$) increase in TLx

Postural sway parameter	Frequency	Horizontal head movement		
		Extension	Neutral	Flexion
TLx (mm)	1595 Hz	141.4 ± 69.3 **	139.6 ± 78.6	127.5 ± 62.2
	2916 Hz	140.7 ± 71.0 ++	121.0 ± 58.6	123.9 ± 61.4
Vxm (mm/s)	1595 Hz	7.10 ± 3.48 **	7.00 ± 3.94	6.40 ± 3.12
	2916 Hz	7.06 ± 3.56 ++	6.07 ± 2.94	6.22 ± 3.08

** significantly ($p<0.01$) greater than flexion.

++ significantly ($p<0.01$) greater than neutral and flexion.

Postural sway parameter	Frequency	Vertical head movement		
		Left	Looking ahead	Right
TLx (mm)	1595 Hz	134.2 ± 56.6	125.8 ± 67.6	132.8 ± 62.7
	2916 Hz	129.2 ± 62.7	129.8 ± 66.9	140.4 ± 67.9 **
Vxm (mm/s)	1595 Hz	6.74 ± 2.84	6.31 ± 3.39	6.66 ± 3.15
	2916 Hz	6.48 ± 3.15	6.51 ± 3.36	7.04 ± 3.40 **

** significanlty greater than looking directly ahead ($p<0.05$) and rotation to the left ($p<0.01$).

Postural sway parameter	Frequency	Diagonal head movement	
		LE	RE
TLx (mm)	1595 Hz	142.7 ± 67.6	138.4 ± 64.5
	2916 Hz	144.4 ± 68.9	132.8 ± 67.0
Vxm (mm/s)	1595 Hz	7.16 ± 3.39	6.94 ± 3.24
	2916 Hz	7.25 ± 3.46	6.66 ± 3.36

Table 8.8 The interaction between sound frequency and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal direction with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the total path length (TLx) and mean sway velocity (Vxm) in the mediolateral direction (mean ± SD).

with neck extension compared with neutral or flexion. For vertical head movement at 1595Hz there was no significant difference in TLx, however, at 2916Hz there was a significant increase with rotation to the right compared with looking directly ahead or with rotation to the left ($p<0.01$). No differences in TLx were observed at either frequency with diagonal head movement. There was a significant increase in TLx with both diagonal head movements compared with horizontal head movement with neck flexion at both frequencies.

A similar pattern was observed for the mean mediolateral sway velocity (Table 8.8).

Interaction between the velocity and direction of head movement

The analyses of variance showed significant interactions between the velocity of head movement and direction of head movement on all sway parameters in the anteroposterior direction, except the COG projection. In addition, significant interactions were observed for TL and Vm. As shown in Table 8.9 horizontal head movement at the lower velocity of movement showed a significant increase in Sy with neck extension compared with neutral ($p<0.01$) and flexion, being due to the increase in both Sa and Sp. With horizontal head movement at the higher velocity a significant ($p<0.01$) increase in Sy with neck extension compared with flexion was observed due to the increase in both Sa and Sp. There was also a significant ($p<0.01$) increase in Sa with neck extension compared with neutral.

No differences in Sy, Sa and Sp were observed for vertical head movement at the lower velocity (Table 8.9). In contrast, at the higher velocity there was a significant ($p<0.01$) reduction in Sy with rotation to the right and left compared with looking directly ahead, the increase being due to the significant ($p<0.01$) increase in both Sa and Sp.

There were no differences in Sy, Sa and Sp at either velocity for diagonal head movements (Table 8.9). Comparing head movement diagonally with that horizontally or vertically, at the lower velocity there was a significant increase in Sy, Sa and Sp for both diagonal head movements compared with horizontal head movement with neck flexion. In addition, there was a significant increase in Sy ($p<0.01$), due to the increase in both Sa and Sp ($p<0.01$), for RE diagonal head movement compared with vertical head movement with rotation to the left.

Postural sway parameter	Velocity of head movement	Horizontal head movement		
		Extension	Neutral	Flexion
Sy (mm)	0.2 m/s	1.36 ± 0.56 **	1.16 ± 0.47	1.22 ± 0.51
	1.0 m/s	1.48 ± 0.53 ++	1.33 ± 0.75	1.28 ± 0.46
Sa (mm)	0.2 m/s	0.67 ± 0.28 **	0.57 ± 0.23	0.61 ± 0.26
	1.0 m/s	0.74 ± 0.27 **	0.64 ± 0.25	0.64 ± 0.24
Sp (mm)	0.2 m/s	0.68 ± 0.30 *	0.58 ± 0.27	0.61 ± 0.27
	1.0 m/s	0.74 ± 0.27 ++	0.69 ± 0.63	0.64 ± 0.24

* $p<0.05$, ** $p<0.01$ significantly greater than neutral and flexion.
++ significantly ($p<0.01$) greater than flexion.

Postural sway parameter	Velocity of head movement	Vertical head movement		
		Left	Looking ahead	Right
Sy (mm)	0.2 m/s	1.31 ± 0.44	1.34 ± 0.42	1.41 ± 0.55
	1.0 m/s	1.72 ± 0.52 **	2.09 ± 0.59	1.75 ± 0.54 **
Sa (mm)	0.2 m/s	0.67 ± 0.24	0.67 ± 0.23	0.69 ± 0.26
	1.0 m/s	0.86 ± 0.27 **	1.08 ± 0.33	0.89 ± 0.28 **
Sp (mm)	0.2 m/s	0.64 ± 0.22	0.67 ± 0.21	0.71 ± 0.30
	1.0 m/s	0.85 ± 0.27 **	1.01 ± 0.27	0.86 ± 0.27 **

** significantly ($p<0.01$) less than looking directly ahead.

Postural sway parameter	Velocity of head movement	Diagonal head movement	
		LE	RE
Sy (mm)	0.2 m/s	1.52 ± 0.59	1.40 ± 0.51
	1.0 m/s	1.80 ± 0.61	1.64 ± 0.57
Sa (mm)	0.2 m/s	0.75 ± 0.30	0.68 ± 0.25
	1.0 m/s	0.90 ± 0.32	0.83 ± 0.31
Sp (mm)	0.2 m/s	0.77 ± 0.31	0.71 ± 0.28
	1.0 m/s	0.90 ± 0.30	0.81 ± 0.27

Table 8.9 **The interaction between velocity of head movement and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of sway in the anteroposterior direction (Sy) (separately anteriorly (Sa) and posteriorly (Sp)) (mean ± SD).**

At the higher velocity (Table 8.9) only LE diagonal head movement significantly increased Sy (p<0.01), Sa and Sp (p<0.01) compared with horizontal head movement with neck extension. There was also a significant (p<0.01) increase in Sy, Sa and Sp for both diagonal head movements compared with horizontal head movement with neck flexion.

Postural sway parameter	Velocity of head movement	Horizontal head movement		
		Extension	Neutral	Flexion
TL (mm)	0.2 m/s	221.9 ± 115.7 * +	205.5 ± 120.8	206.3 ± 106.6
	1.0 m/s	247.3 ± 116.9 ** ++	219.7 ± 107.2	218.5 ± 106.2
TLy (mm)	0.2 m/s	137.3 ± 83.5 ** +	121.3 ± 80.0	126.2 ± 78.4
	1.0 m/s	149.0 ± 83.3 ** +	129.6 ± 75.7	133.6 ± 77.1

* p<0.05, ** p<0.01 significantly greater than neutral.
\+ p<0.05, ++ p<0.01 significantly greater than flexion.

Postural sway parameter	Velocity of head movement	Vertical head movement		
		Left	Looking ahead	Right
TL (mm)	0.2 m/s	211.2 ± 98.5	214.8 ± 111.9	224.2 ± 113.3 **
	1.0 m/s	241.9 ± 105.1 *	257.5 ± 108.2	250.1 ± 111.3
TLy (mm)	0.2 m/s	130.0 ± 70.4	136.9 ± 81.0	139.9 ± 81.1
	1.0 m/s	154.9 ± 76.7 **	177.9 ± 75.2	162.1 ± 82.7 *

* p<0.05, ** p<0.01 significantly greater or less than looking directly ahead.

Postural sway parameter	Velocity of head movement	Diagonal head movement	
		LE	RE
TL (mm)	0.2 m/s	238.4 ± 122.7	223.9 ± 110.0
	1.0 m/s	257.0 ± 107.5	246.6 ± 118.1
TLy (mm)	0.2 m/s	147.5 ± 82.7	140.6 ± 82.7
	1.0 m/s	165.9 ± 82.3	158.5 ± 89.4

Table 8.10 The interaction between velocity of head movement and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the total path length (TL) and path length in the anteroposterior direction (TLy) (mean ± SD).

As shown in Table 8.10 horizontal head movement at the lower velocity resulted in a significant increase in TL and TLy (p<0.01) with neck extension compared with neutral. In addition, there was significant increase in TL and TLy with extension compared with flexion. At the higher velocity of movement there were significant (p<0.01) increases in TL and TLy with neck extension compared with neutral, as well as a significant increase in TL ($p<0.01$) and TLy compared flexion.

Vertical head movement (Table 8.10) at the lower velocity resulted in a significant ($p<0.01$) increase in TL with rotation to the right compared with looking directly ahead. At the higher velocity there was a significant decrease in TL with rotation to the left compared with looking directly ahead. There was also a significant decrease in TLy with rotation to the left ($p<0.01$) as well as to the right compared with looking directly ahead.

There were no differences in TL or TLy for diagonal head movement at either velocity of movement (Table 8.10). At the lower velocity there was a significant increase in TL and TLy for both diagonal head movements compared with horizontal head movement with neck flexion. There was also a significant ($p<0.01$) increase in TL and TLy for LE diagonal head movement compared with vertical head movement with rotation to the left. At the higher velocity there was a significant ($p<0.01$) increase in TL and TLy for both diagonal head movements compared with that horizontally with neck flexion.

The findings for Vm and Vym (Table 8.11) corresponded with the observations for the total path length (TL) and the path length in the anteroposterior direction (TLy).

Postural sway parameter	Velocity of head movement	Horizontal head movement		
		Extension	Neutral	Flexion
Vm (mm/s)	0.2 m/s	11.1 ± 5.80 * +	10.3 ± 6.06	10.4 ± 5.35
	1.0 m/s	12.4 ± 5.87 ** ++	11.0 ± 5.38	11.0 ± 5.33
Vym (mm/s)	0.2 m/s	6.89 ± 4.19 ** +	6.08 ± 4.01	6.33 ± 3.94
	1.0 m/s	7.48 ± 4.19 ** +	6.50 ± 3.80	6.71 ± 3.87

* $p<0.05$, ** $p<0.01$ significantly greater than neutral.
+ $p<0.05$, ++ $p<0.01$ significantly greater than flexion.

Postural sway parameter	Velocity of head movement	Vertical head movement		
		Left	Looking ahead	Right
Vm (mm/s)	0.2 m/s	10.6 ± 4.94	10.8 ± 5.62	11.2 ± 5.68 **
	1.0 m/s	12.1 ± 5.27 *	12.9 ± 5.43	12.6 ± 5.58
Vym (mm/s)	0.2 m/s	6.53 ± 3.53	6.87 ± 4.07	7.02 ± 4.07
	1.0 m/s	7.77 ± 3.85 **	8.93 ± 3.77	8.14 ± 4.15 *

* $p<0.05$, ** $p<0.01$ significantly greater or less than looking directly ahead.

Postural sway parameter	Velocity of head movement	Diagonal head movement	
		LE	RE
Vm (mm/s)	0.2 m/s	12.0 ± 6.16	11.2 ± 5.52
	1.0 m/s	12.9 ± 5.39	12.4 ± 5.93
Vym (mm/s)	0.2 m/s	7.40 ± 4.15	7.05 ± 4.15
	1.0 m/s	8.33 ± 4.13	7.95 ± 4.49

Table 8.11 The interaction between velocity of head movement and horizontal head movement with the neck extended, in neutral and flexed, vertical direction with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the mean velocity of sway (Vm) and sway velocity in the anteroposterior direction (Vym) (mean ± SD).

8.4 Discussion

The findings of this study show that sex, velocity and the direction of head movement all influence postural sway behaviour. In addition, there are important interactions between sex and the velocity of head movement and the combination of velocity and direction of head movement. Although sound per se appears to have no influence on the postural sway behaviour in conditions of dynamic stimulation, there are important interactions between both sound and the velocity of head movement and sound and the direction of head movement.

There was an influence of gender on the COG projection in the mediolateral direction, being greater in females. This finding conflicts with that observed in young adults by Soames and Atha (1978) and Kollegger et al. (1992). The difference may be due to the conditions under which the experiment was undertaken. Thus, it is suggested that the effect of gender on postural sway behaviour and postural control is dependent on the environmental conditions. When standing with feet together lateral sway is markedly reduced by visual feedback (Kollegger et al. 1989), being a more important stabilising factor in males than females (Kollegger et al. 1992).

The velocity of head movement influences the magnitude of sway, the total path length and the mean velocity of sway in both the mediolateral and anteroposterior directions: the greater the velocity of movement, the greater the postural sway. These findings are similar to those reported in Experiment 2 (Chapter 5). Receptors associated with the vestibular system are stimulated by head movement (Carpenter 1990; Livingston 1990; Pansky et al. 1992). Furthermore, Perlmutter et al. (1999) report that the responses of vestibulospinal neurones depends on the frequency of stimulation. Thus, it is feasible that the higher velocity of head movement leads to an increase in postural sway due to the greater vestibular stimulation than represent at the lower velocity.

The direction of head movement was observed to have an effect on most postural sway behaviour parameters. In particular, horizontal movement of the head with the neck extended causes postural instability. Although head movement with the neck extended increases the magnitude of sway, total path length and the mean velocity of sway, there was no change in the COG projection in either the mediolateral or anteroposterior directions. However, with the neck flexed the COG projection moves backward, this may be to act as a counterbalance between the head and the lower limbs following forward movement of the head, consequently, the trunk and lower limbs move backward to help maintain balance and the control of posture. Under static head conditions the postural stability induced by neck extension decreases suggesting that the otoliths are in a disadvantageous position (Jackson and Epstein 1991). In this experiment it is indicated that the mechanism of neck extension and flexion influencing the vestibular system input on postural control is different. Vertical head movement destabilises posture in the mediolateral direction, but stabilises it in the anteroposterior direction. It has been reported that vibration to one side of the neck influences the lateral component of the postural response (Smetanin et al. 1993). It is possible, therefore that neck proprioceptor input is more powerful than vestibular input. An alternative view is that the vestibular system is in balance with reciprocal head movement with the neck extended leaving posture dependent on neck proprioceptive information. The stability that occurs in the anteroposterior direction may be explained by continuous vertical head movement with the disadvantageous position of the vestibular system due to the head being extended (Jackson and Epstein 1991) being countered by the new orientation of the vestibular system with the neck flexed. It is suggested that neck proprioceptor input causes postural instability in the mediolateral direction, but leads to postural stability in the anteroposterior direction. When comparing diagonal head movements with horizontal and vertical movements the findings show the vestibular and neck proprioceptor input to be additive, confirming the observation of Karnath et al. (1994), and depend on the vestibular input, particularly in the anteroposterior direction. The interaction between vestibular and neck proprioceptor inputs acts to destabilise posture.

The interaction between the velocity and direction of head movement only appears to be important in the anteroposterior direction. With horizontal head movement the difference in velocity of movement shows in the anteroposterior sway magnitude, being due to the differences in posterior sway. Thus, the vestibular input controlling the anteroposterior direction appears to depend on the velocity of head movement, with the higher velocity leading to greater posterior sway. With vertical head movement the higher velocity of movement leads to postural stabilisation. It, therefore appears that the vestibular system supports the stabilising effect of neck proprioception in controlling sway behaviour in the anteroposterior direction. From the diagonal head movement findings the neck proprioceptive input appears to be a disturbing factor in the interaction between vestibular and the neck proprioceptor system.

Unexpectedly, sound was observed to have no effect on postural sway behaviour. This finding is not the same as that reported in Experiment 3 (Chapter

7) and in previous studies (Juntunen et al. 1987; Raper and Soames 1991; Kilburn et al. 1992; Soames and Raper 1992; Sakellari and Soames 1996). The difference may be due to the conditions of the experiment, in which static stimulation was used in the previous studies with dynamic stimulation in the current experiment. It is suggested that head movement can counter the destabilising effect of sound on postural control.

The interaction between sound and direction of head movement was seen to only influence mediolateral sway. With horizontal head movement the interaction between vestibular stimulation and sound caused postural destabilisation. The exposure to noise inducing body sway thereby suggesting some disturbance of the vestibular system (Juntunen et al. 1987). It is possible that the inappropriate auditory input disturbs the vestibular system and, as a result, the vestibular input becomes unbalanced. Although there was no effect of frequency alone on postural sway, the interaction between frequency and horizontal head movement shows a greater postural instability at the higher frequency. It is, therefore suggested that the interaction between the vestibular and auditory systems is additive and appears to depend on the auditory input. For vertical movement the interaction between the neck proprioceptor and auditory systems leads to mediolateral instability. The auditory input has been reported to control postural maintenance in the mediolateral direction (Sakellari and Soames 1996). In addition, in this experiment neck proprioception increases the magnitude of mediolateral sway. Thus, it is suggested that the interaction between neck proprioception and the auditory system is additive. However, at the higher frequency there is no difference in sway with any neck position. It is possible that sound reduces the destabilising effect of neck proprioceptor input on postural control. It is, therefore suggested that the interaction between neck proprioception and auditory input depends on auditory stimuli. For diagonal head movement there is an interaction between the vestibular, neck proprioceptor and auditory system. In such an interaction neck proprioceptive input appears to be the destabilising factor leading to a decrease in postural stability, since at certain frequencies neck rotation with neck flexion/extension causes greater sway behaviour than does neck flexion/extension alone.

8.5 Summary

During auditory stimulation the responses to dynamic vestibular and neck proprioceptor stimulation have an influence on postural control and postural behaviour. The vestibular input depends on the frequency of stimulation i.e. the velocity of head movement. The vestibular input associated with neck extension causes postural instability, whereas that associated with neck flexion leads to postural stability. Neck proprioceptor input destabilises posture in the mediolateral direction but stabilises it in the anteroposterior direction. The interaction between the vestibular and neck proprioceptor systems is additive and depends on the vestibular input. Although the auditory system alone has no influence on postural sway behaviour, there are vestibular-auditory, neck proprioceptor-auditory and vestibular-neck proprioceptor-auditory interactions which all influence mediolateral sway behaviour. The interaction between the vestibular and auditory systems decreases postural stability due to the additive effect of each input on posture: such an interaction appears to depend on the auditory stimuli. The interaction between neck proprioceptor and auditory inputs also depends on the influence of the auditory input. The interaction between the vestibular, neck proprioceptor and auditory systems destabilises posture, which is due to the destabilising effect of neck proprioception on mediolateral sway.

Chapter 9

Responses to static and dynamic vestibular and neck proprioceptor stimulation and auditory stimulation

9.1 Introduction

As demonstrated by Raper and Soames (1991) auditory stimulation can have a destabilising effect on postural control. Exposure to chronic noise is known to decrease postural stability, possibly by affecting the vestibular system (Juntunen et al. 1987) or by damaging the receptors of the eighth nerve (Kilburn et al. 1992). However, the effect of sound on postural behaviour appears to have stabilising and destabilising effects depending on the frequency (Sakellari and Soames 1996). Balance is influenced by the vestibular (Keshner et al. 1987; Horak et al. 1990) and neck proprioceptor (Koskimies et al. 1997) systems. Anatomic studies have revealed an interaction between vestibular and neck proprioceptor input (Anastasopoulus and Mergner 1982). Static and dynamic stimulation of the vestibular and neck proprioceptors have been examined in the Experiments in Chapter 7 and 8, respectively. However, the question arises as to whether there is a difference in response to static and dynamic stimulation of the vestibular and neck proprioceptor systems in the presence of auditory stimulation. The aim in this chapter is to examine the influence of static and dynamic stimulation of the vestibular, as well as the neck proprioceptors and auditory stimulation on postural sway behaviour.

9.2 Materials and methods

The data from thirty subjects (15 females, 15 males) who participated in both Experiments 3 (Chapter 7) and 4 (Chapter 8) was analysed and compared.

The manipulation of the data obtained from the Experiment 3 (Chapter 7) is as described for the data in the Experiment 1 (Chapter 4) outlined in Chapter 6 (details in Chapter 6 part 6.2). The data from Experiment 3 (Chapter 7) is the static stimulation at the frequencies 1595Hz and 2916Hz, while that from the Experiment 4 (Chapter 8) is the dynamic stimulation at the same frequencies.

Four-way analyses of variance were conducted for each of the sway parameters (Chapter 3 part 3.3) with sex, sound, the velocity and direction of head movement as independent variables in order to determine the influence of each on postural sway behaviour. t-tests were conducted as appropriate to determine the significant differences for each group of independent variables. Unless otherwise stated all differences are at the 5% level of significance.

9.3 Result

9.3.1 Subject characteristics

Since the population studied was in the same for Experiments 3 (Chapter 7) and 4 (Chapter 8), the characteristics of the population are the same as those given in Table 7.1 (page 96).

9.3.2 Analyses of variance

The analyses of variance showed that sex, the velocity (static/dynamic stimulation) and direction of head movement as well as their interactions, and the combination between these and sound all influence postural sway behaviour (Appendix 10).

Sex

Few differences in sway behaviour were observed between the males and females, the difference being restricted to X. There was a significant ($p<0.01$) shift of the COG projection to the right in females (4.02 ± 2.37) compared with males (2.18 ± 2.01).

Static/dynamic head condition

The velocity of head movement influenced all sway behaviour parameters

Postural sway parameter	Head condition		
	Static	Dynamic	
		0.2 m/s	1.0 m/s
X (mm)	3.39 ± 2.41	2.97 ± 2.36	2.94 ± 2.35
Y (mm)	0.07 ± 1.94	-0.16 ± 1.87	-0.12 ± 1.85
Sx (mm)	1.16 ± 0.50	1.59 ± 0.60 **	1.76 ± 0.65 ++
Sr (mm)	0.59 ± 0.29	0.80 ± 0.31 **	0.87 ± 0.34 ++
Sl (mm)	0.58 ± 0.23	0.79 ± 0.30 **	0.88 ± 0.33 ++
Sy (mm)	0.91 ± 0.33	1.34 ± 0.52 **	1.64 ± 0.62 ++
Sa (mm)	0.45 ± 0.16	0.67 ± 0.26 **	0.82 ± 0.31 ++
Sp (mm)	0.46 ± 0.18	0.67 ± 0.28 **	0.81 ± 0.35 ++
TL (mm)	173.9 ± 116.2	218.3 ± 112.3 **	242.3 ± 110.3 ++
TLx (mm)	99.8 ± 68.9	128.2 ± 66.4 **	139.9 ± 64.9 ++
TLy (mm)	106.1 ± 77.7	135.0 ± 79. 9 **	154.0 ± 81.3 ++
Vm (mm/s)	8.73 ± 5.83	10.95 ± 5.64 **	12.16 ± 5.53 ++
Vxm (mm/s)	5.02 ± 3.45	6.43 ± 3.33 **	7.02 ± 3.26 ++
Vym (mm/s)	5.33 ± 3.90	6.77 ± 4.01 **	7.73 ± 4.08 ++
Ay (°)	-16.2 ± 47.3	-14.8 ± 37.0	-13.1 ± 32.6

** significantly ($p<0.01$) greater than static.

++ significantly ($p<0.01$) greater than static and dynamic at 0.2m/s.

Table 9.1 The influence of static/dynamic head condition on the centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions, magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), total path length (TL), mediolateral (TLx) and anteroposterior (TLy) path lengths, mean velocity of sway (Vm), mediolateral (Vxm) and anteroposterior (Vym) sway velocities, and angle of sway from the sagittal plane (Ay) (mean ± SD).

except X, Y and Ay (Table 9.1) There were significant ($p<0.01$) increases in the magnitudes of sway, path lengths and velocities for both the mediolateral and anteroposterior directions for the dynamic compared with the static condition. In addition, the sway parameters were also significantly ($p<0.01$) greater at the higher velocity of movement than the lower.

Direction of head movement

The direction of head movement influenced all postural sway parameter except X and Ay. As shown in Table 9.2 there were significant differences in Y for horizontal head movement with neck extension or flexion resulting in a posterior shift of the COG projection compared with neutral. No differences were observed with vertical and diagonal head movements.

Postural sway parameter	**Horizontal head movement**		
	Extension	**Neutral**	**Flexion**
Y (mm)	-0.06 ± 1.89 *	0.03 ± 1.86	-0.10 ± 1.96 *

* significantly ($p<0.05$) less than neutral.

Postural sway parameter	**Vertical head movement**		
	Left	**Looking ahead**	**Right**
Y (mm)	-0.06 ± 1.84	-0.12 ± 1.87	-0.04 ± 1.90

Postural sway parameter	**Diagonal head movement**	
	LE	**RE**
Y (mm)	-0.16 ± 1.84 **	-0.07 ± 1.98 **, ++

** significantly ($p<0.01$) less than vertical head movement with rotation to the left.

++ significantly ($p<0.01$) less than vertical head movement with rotation to the right.

Table 9.2 **The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the anteroposterior centre of gravity projection (Y) (mean ± SD).**

There was no difference between head movement diagonally and horizontally (Table 9.2). However, a significant ($p<0.01$) posterior shift of the

COG with both diagonal head movements compared with vertical head movement with rotation to the left was observed. In addition, only RE diagonal head movement significantly ($p<0.01$) showed a posterior shift of the COG projection compared with vertical head movement with rotation to the right.

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
Sx (mm)	1.57 ± 0.81 *	1.45 ± 0.68	1.47 ± 0.56
Sr (mm)	0.79 ± 0.42 *	0.73 ± 0.36	0.73 ± 0.30
Sl (mm)	0.78 ± 0.40	0.73 ± 0.34	0.74 ± 0.28

* significantly ($p<0.05$) greater than neutral.

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
Sx (mm)	1.50 ± 0.58	1.43 ± 0.56	1.52 ± 0.60 *
Sr (mm)	0.75 ± 0.30	0.72 ± 0.30	0.77 ± 0.34 *
Sl (mm)	0.75 ± 0.29	0.72 ± 0.27	0.75 ± 0.28

* significantly ($p<0.05$) greater than looking directly ahead.

Postural sway parameter	Diagonal head movement	
	LE	RE
Sx (mm)	1.59 ± 0.67 * ++	1.50 ± 0.58
Sr (mm)	0.79 ± 0.34 * +	0.76 ± 0.31
Sl (mm)	0.80 ± 0.35 ** +	0.74 ± 0.29

* $p<0.05$, ** $p<0.01$ significantly greater than horizontal head movement with flexion.
+ $p<0.05$, ++ $p<0.01$ significantly greater than vertical head movement with rotaion to the left.

Table 9.3 **The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of mediolateral sway (Sx) (separately to the right (Sr) and left (Sl)) (mean $\pm$ SD).**

As shown in Table 9.3 for horizontal head movement there was a significant increase in Sx and Sr with neck extension compared with neutral, similarly, with vertical movement there was a significant increase in Sx and Sr with rotation to the right compared with looking directly ahead. No significant differences were observed with diagonal head movement for Sx, Sr or Sl. There was a significant increase in Sx, Sr and Sl ($p<0.01$) for LE diagonal head movement compared with horizontal head movement with neck flexion and a significant increase in Sx (p<0.01), Sr and Sl compared with vertical head movement with rotation to the left.

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
Sy (mm)	1.24 ± 0.54	1.13 ± 0.57	1.15 ± 0.45 **
Sa (mm)	0.61 ± 0.28	0.55 ± 0.23 **	0.58 ± 0.23 *
Sp (mm)	0.62 ± 0.28	0.58 ± 0.42	0.58 ± 0.24 **

* p<0.05, ** p<0.01 significantly less than extension.

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
Sy (mm)	1.31 ± 0.54 **	1.45 ± 0.66	1.36 ± 0.61 *
Sa (mm)	0.66 ± 0.28 **	0.73 ± 0.36	0.68 ± 0.30 *
Sp (mm)	0.65 ± 0.27 **	0.72 ± 0.31	0.68 ± 0.31

* p<0.05, ** p<0.01 significantly less than looking directly ahead.

Postural sway parameter	Diagonal head movement	
	LE *	RE *
Sy (mm)	1.40 ± 0.64 ** ++	1.32 ± 0.56
Sa (mm)	0.70 ± 0.33 ** +	0.65 ± 0.29
Sp (mm)	0.71 ± 0.33 ** +	0.67 ± 0.28

* significantly (p<0.01) greater than horizontal head movement with flexion.
** significantly (p<0.01) greater than horizontal head movement with extension.
+ p<0.05, ++ p<0.01 significantly greater than vertical head movement with rotation to the left.

Table 9.4 **The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)) (mean ± SD).**

As shown in Table 9.4 for horizontal head movement there was a significant increase in Sy (p<0.01), Sa and Sp (p<0.01) with neck extension compared with flexion. In addition, there was a significant (p<0.01) increase in Sa with extension compared with neutral. For vertical head movement there was a significant decrease in Sy with rotation to the right compared with looking directly ahead, being due to the significant reduction in Sa. There was also a significant (p<0.01) decrease in Sy, Sa and Sp with rotation to the left compared with looking directly ahead. No differences were observed for diagonal head movements. There was a significant (p<0.01) increase in Sy, Sa and Sp with both diagonal head movements compared with horizontal head movement with neck flexion. Furthermore, for LE diagonal head movement a significant (p<0.01) increase in Sy, Sa and Sp was observed when compared with horizontal head movement with neck extension and a significant increase in Sy (p<0.01), Sa and Sp when compared with vertical head movement with rotation to the left.

Postural sway parameter	**Horizontal head movement**		
	Extension	**Neutral**	**Flexion**
TL (mm)	214.1 ± 123.3	200.5 ± 113.7 **	199.0 ± 104.7 **
TLx (mm)	126.9 ± 74.4	120.9 ± 70.1	116.5 ± 59.6 **
TLy (mm)	130.9 ± 85.7	119.2 ± 75.6 **	121.8 ± 75.8 **

** significantly (p<0.01) less than extension.

Postural sway parameter	**Vertical head movement**		
	Left	**Looking ahead**	**Right**
TL (mm)	206.7 ± 101.6	213.1 ± 110.6	220.6 ± 137.0
TLx (mm)	118.7 ± 58.4	116.5 ± 64.2	128.5 ± 83.2 **
TLy (mm)	129.5 ± 73.4 *	139.4 ± 80.2	137.8 ± 93.1

* p<0.05, ** p<0.01 significantly greater or less than looking directly ahead.

Postural sway parameter	**Diagonal head movement**	
	LE	**RE**
TL (mm)	221.8 ± 116.8 **	216.2 ± 119.4 **
TLx (mm)	128.0 ± 68.1 **	124.8 ± 69.1 **
TLy (mm)	139.2 ± 82.8 **	135.6 ± 86.4 **

** significantly (p<0.01) greater than horizontal head movement with flexion and vertical head movement with rotation to the left.

Table 9.5 **The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the total path length (TL) and path length in the mediolateral (TLx) and anteroposterior (TLy) directions (mean ± SD).**

As shown in Table 9.5 for horizontal head movement there was a significant (p<0.01) increase in TL, TLx and TLy with neck extension compared with flexion and a significant (p<0.01) increase in TL with neck extension compared with neutral. This latter increase was due to the significant (p<0.01) increase in TLy. For vertical head movements there was a significant (p<0.01) increase in TLx with rotation to the right, but a significant decrease in TLy with rotation to the left, compared with looking directly ahead. No differences were observed for diagonal head movement. There were significant (p<0.01) increases in TL, TLx and TLy for both diagonal head movements compared with horizontal head movement with neck flexion and vertical head movement with rotation to the left. A similar pattern was observed for Vm, Vxm and Vym (Table 9.6).

Postural sway parameter	**Horizontal head movement**		
	Extension	**Neutral**	**Flexion**
Vm (mm/s)	10.7 ± 6.19	10.1 ± 5.71 **	9.99 ± 5.25 **
Vxm (mm/s)	6.38 ± 3.72	6.07 ± 3.52	5.85 ± 2.99 **
Vym (mm/s)	6.57 ± 4.30	5.98 ± 3.79 **	6.11 ± 3.80 **

** significantly (p<0.01) less than extension.

Postural sway parameter	**Vertical head movement**		
	Left	**Looking ahead**	**Right**
Vm (mm/s)	10.4 ± 5.10	10.7 ± 5.55	11.1 ± 6.88
Vxm (mm/s)	5.97 ± 2.91	5.85 ± 3.22	6.45 ± 4.18 **
Vym (mm/s)	6.50 ± 3.68 *	7.00 ± 4.02	6.92 ± 4.67

* p<0.05, ** p<0.01 significantly greater or less than looking directly ahead.

Postural sway parameter	**Diagonal head movement**	
	LE	**RE**
Vm (mm/s)	11.1 ± 5.86 **	10.8 ± 5.99 **
Vxm (mm/s)	6.42 ± 3.42 **	6.26 ± 3.47 **
Vym (mm/s)	6.99 ± 4.16 **	6.80 ± 4.33 **

** significantly (p<0.01) greater than horizontal head movement with flexion and vertical head movement with rotation to the left.

Table 9.6 **The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the mean velocity of sway (Vm) and mean sway velocity in the mediolateral (Vxm) and anteroposterior (Vym) directions (mean ± SD).**

Interaction between sex and direction of head movement

A significant interaction between sex and the direction of head movement was observed for Y only. As shown in Table 9.7 in females for horizontal head movement there was a significant ($p<0.01$) posterior shift of the COG projection with neck extension and flexion compared with neutral, while with vertical head movement there was a significant anterior shift of the COG projection with rotation either to the right or left compared with looking directly ahead. In contrast, no differences were observed in males. There was no difference for diagonal head movement for either sex.

Postural sway parameter	**Sex**	**Horizontal head movement**		
		Extension	**Neutral**	**Flexion**
Y (mm)	Females	-0.18 ± 1.77 **	0.03 ± 1.83	-0.22 ± 1.85 **
	Males	0.07 ± 2.00	0.04 ± 1.90	0.02 ± 2.06

** significantly ($p<0.01$) less than neutral.

Postural sway parameter	**Sex**	**Vertical head movement**		
		Left	**Looking ahead**	**Right**
Y (mm)	Females	-0.09 ± 1.74 *	-0.17 ± 1.79	-0.07 ± 1.84 *
	Males	-0.04 ± 1.95	-0.07 ± 1.95	-0.01 ± 1.98

* significantly ($p<0.05$) greater than looking directly ahead.

Postural sway parameter	**Sex**	**Diagonal head movement**	
		LE	**RE**
Y (mm)	Females	-0.10 ± 1.88	-0.13 ± 1.79
	Males	-0.04 ± 2.08	-0.18 ± 1.91

Table 9.7 **The interaction between sex and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the anteroposterior centre of gravity projection (Y) (mean ± SD).**

No differences were observed for females for diagonal head movement compared with horizontal or vertical head movement (Table 9.7). However, in males there was a significant posterior shift of the COG projection for RE diagonal head movement compared with horizontal head movement with neck extension and flexion and vertical head movement with rotation to the right and left.

Interaction between sound and static/dynamic head condition

Significant interactions between sound and static/dynamic head movement were observed for Sx, Sr, Sl and Sa only. Although the initial analysis of variance showed a significant interaction between sound and static/dynamic head condition, the differences were between inappropriate comparisons, i.e. at 1595Hz with static head condition compared with 2916Hz at 0.2m/s velocity of movement.

Interaction between sex and sound and static/dynamic head condition

The only parameter to show a significant interaction between sex, sound and static/dynamic head condition was Sp. Although the initial analysis of variance showed a significant interaction between sex and sound and static/dynamic head condition, the differences were between inappropriate comparisons, i.e. males at 1595Hz with 0.2m/s velocity of movement compared with females at 2916Hz with the static head condition.

Interaction between sound and direction of head movement

The analyses of variance showed a significant interaction between sound and direction of head movement for Sx, Sr and Sl. As shown in Table 9.8 for horizontal head movement at 1595Hz there were no differences, however, at 2916Hz there was a significant ($p<0.01$) increase in Sx, Sr and Sl with neck extension compared with neutral. In addition, there was a significant increase in Sx with neck flexion compared with neutral, being due to the significant increase in Sl. For vertical head movement at 1595Hz there was a significant ($p<0.01$) increase in Sx with rotation to the left, due to the significant ($p<0.01$) increase in Sr and Sl, and a significant increase in Sx with rotation to the right, due to the significant ($p<0.01$) increase in Sr, compared with looking directly ahead. At 2916Hz no differences in Sx, Sr and Sl were observed.

Postural sway parameter	Frequency	Horizontal head movement		
		Extension	Neutral	Flexion
Sx (mm)	1595 Hz	1.53 ± 0.71	1.52 ± 0.76	1.44 ± 0.54
	2916 Hz	1.61 ± 0.90 **	1.38 ± 0.59	1.50 ± 0.59 *
Sr (mm)	1595 Hz	0.77 ± 0.36	0.76 ± 0.39	0.73 ± 0.29
	2916 Hz	0.81 ± 0.47 **	0.69 ± 0.32	0.74 ± 0.30
Sl (mm)	1595 Hz	0.76 ± 0.35	0.76 ± 0.38	0.71 ± 0.26
	2916 Hz	0.80 ± 0.44 **	0.69 ± 0.30	0.76 ± 0.30 *

* $p<0.05$, ** $p<0.01$ significantly greater than neutral.

Postural sway parameter	Frequency	Vertical head movement		
		Left	Looking ahead	Right
Sx (mm)	1595 Hz	1.53 ± 0.59 **	1.38 ± 0.51	1.47 ± 0.57 *
	2916 Hz	1.48 ± 0.56	1.48 ± 0.61	1.56 ± 0.64
Sr (mm)	1595 Hz	0.76 ± 0.30 **	0.69 ± 0.25	0.75 ± 0.31 **
	2916 Hz	0.74 ± 0.30	0.75 ± 0.34	0.78 ± 0.36
Sl (mm)	1595 Hz	0.77 ± 0.30 **	0.70 ± 0.27	0.72 ± 0.26
	2916 Hz	0.73 ± 0.28	0.73 ± 0.28	0.78 ± 0.30

* $p<0.05$, ** $p<0.01$ significantly greater than looking directly ahead.

Postural sway parameter	Frequency	Diagonal head movement	
		LE	RE
Sx (mm)	1595 Hz	1.59 ± 0.70	1.51 ± 0.58
	2916 Hz	1.59 ± 0.65	1.49 ± 0.59
Sr (mm)	1595 Hz	0.79 ± 0.34	0.76 ± 0.31
	2916 Hz	0.79 ± 0.35	0.76 ± 0.32
Sl (mm)	1595 Hz	0.80 ± 0.37	0.75 ± 0.29
	2916 Hz	0.80 ± 0.33	0.73 ± 0.29

Table 9.8 **The interaction between sound frequency and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of mediolateral sway (Sx) (separately to the right (Sr) and left (Sl)) (mean ± SD).**

There were no differences in Sx, Sr and Sl at either frequency with diagonal head movements (Table 9.8). However, at 1595Hz there was a significant ($p<0.01$) increase in Sx, due to the significant increase in Sr, for LE diagonal head movement compared with horizontal head movement with neck flexion. No differences in Sx, Sr and Sl were observed between diagonal and vertical head movements. At 2916Hz there were no differences for diagonal head movement compared with horizontal head movement. In contrast, a significant increase in Sx, due to the significant ($p<0.01$) increase in Sl, was observed for LE diagonal head movement compared with vertical head movement with rotation to the left.

Interaction between sex and sound and direction of head movement

A significant interaction between sex, sound and direction of head movement was observed for X only. As shown in Table 9.9 for horizontal head movement at both frequencies there was no difference in females. In contrast, in males (Table 9.9) there was significant shift of the COG projection to the left with neck extension and flexion compared with neutral at 1595Hz. In addition, at 2916Hz there was also a significant shift the COG projection to the left with neck flexion compared with extension. No differences in X were observed for vertical or diagonal head movements, or between head movements diagonally, horizontally or vertically at either sound frequency in females or males.

Postural sway parameter	Frequency	Horizontal head movement		
		Extension	Neutral	Flexion
Females				
X (mm)	1595 Hz	4.07 ± 2.72	4.14 ± 2.65	3.77 ± 2.83
	2916 Hz	4.00 ± 2.06	4.19 ± 2.05	3.89 ± 2.18
Males				
X (mm)	1595 Hz	2.04 ± 2.09 *	2.28 ± 2.26	2.00 ± 2.15 *
	2916 Hz	2.25 ± 1.83	2.20 ± 1.65	2.09 ± 1.79 +

* significantly ($p<0.05$) less than neutral.

+ significantly ($p<0.05$) less than extension.

Postural sway parameter	Frequency	Vertical head movement		
		Left	Looking ahead	Right
Females				
X (mm)	1595 Hz	3.92 ± 2.68	4.16 ± 2.74	4.12 ± 2.57
	2916 Hz	4.08 ± 1.99	4.03 ± 2.10	4.17 ± 2.08
Males				
X (mm)	1595 Hz	2.17 ± 2.09	1.88 ± 2.15	2.26 ± 2.13
	2916 Hz	2.28 ± 1.72	2.12 ± 1.96	2.45 ± 1.86

Postural sway parameter	Frequency	Diagonal head movement	
		LE	RE
Females			
X (mm)	1595 Hz	3.83 ± 2.60	3.74 ± 2.76
	2916 Hz	4.10 ± 1.99	4.09 ± 1.91
Males			
X (mm)	1595 Hz	2.17 ± 2.36	2.09 ± 2.19
	2916 Hz	2.26 ± 2.00	2.29 ± 1.97

Table 9.9 **The interaction between sex, sound frequency and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the mediolateral centre of gravity projection (X) (mean ± SD).**

Interaction between static/dynamic head condition and direction of head movement

Significant interactions between static/dynamic head condition and direction of head movement were observed for all postural sway behaviour parameters except X (Table 9.10).

Postural sway parameter	Head condition	Horizontal head movement		
		Extension	Neutral	Flexion
Y (mm)	Static	0.07 ± 2.02	0.09 ± 1.80	0.06 ± 2.07
	0.2 m/s	-0.18 ± 1.84 *	0.00 ± 1.95	-0.23 ± 1.92 *
	1.0 m/s	-0.05 ± 1.84	0.02 ± 1.84	-0.13 ± 1.89

* significantly ($p<0.05$) less than neutral.

Postural sway parameter	Head condition	Vertical head movement		
		Left	Looking ahead	Right
Y (mm)	Static	-0.03 ± 1.89 **	0.07 ± 2.07 *	0.18 ± 1.96
	0.2 m/s	-0.11 ± 1.81	-0.21 ± 1.72	-0.15 ± 1.87
	1.0 m/s	-0.06 ± 1.86	-0.23 ± 1.81	-0.13 ± 1.89

* $p<0.05$, ** $p<0.01$ significantly less than rotation to the right.

Postural sway parameter	Head condition	Diagonal head movement	
		LE	RE
Y (mm)	Static	0.10 ± 2.04	0.00 ± 1.78
	0.2 m/s	-0.10 ± 2.11	-0.28 ± 1.84
	1.0 m/s	-0.20 ± 1.79	-0.19 ± 1.93

Table 9.10 The interaction between static/dynamic head condition and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the anteroposterior centre of gravity projection (Y) (mean ± SD).

As shown in Table 9.10 for horizontal head movement there were no significant differences in Y for the static head condition or at the higher velocity of movement. In contrast, at the lower velocity there was a significant shift of the COG projection posteriorly with neck extension and flexion compared with neutral. With vertical head movement there was a significant posterior shift of the COG projection when looking directly ahead or with rotation to the left ($p<0.01$)

compared with rotation to the right in the static head condition: no differences in Y were observed for either dynamic head condition. With diagonal head movement no differences in Y were observed. No differences in Y were observed between head movement diagonally and horizontally for the static condition. However, there was a significant ($p<0.01$) anterior shift of the COG projection for LE diagonal head movement compared with vertical head movement with rotation to the left. In addition, a significant ($p<0.01$) posterior shift of the COG projection was observed for RE diagonal head movement compared with vertical head movement with rotation to the right. No differences in Y were observed between head movement diagonally and horizontally or vertically for either dynamic head condition.

Table 9.11 shows that for horizontal head movement there was a significant ($p<0.01$) decrease in Sx, Sr and Sl in the static head condition with neck extension compared with neutral (Sx and Sr, $p<0.01$) or flexion. In contrast, no significant difference in Sx at the lower velocity of head movement was observed, but at the higher velocity there was a significant increase in Sx, Sr and Sl with extension compared with neutral and flexion (Sx and Sl, $p<0.01$). For vertical and diagonal head movement no difference in Sx, Sr and Sl at the static head condition or at either velocity of movement were observed. For the static head condition there was a significant ($p<0.01$) increase in Sx and Sr for RE diagonal head movement and Sl for both diagonal head movements compared with horizontal head movement with neck extension. In contrast, there was a significant ($p<0.01$) decrease in Sx and Sr for LE diagonal head movement and in Sl for both diagonal head movements compared with horizontal head movement with neck flexion.

At the lower velocity of head movement there was a significant increase in Sx, Sr and Sl for LE diagonal head movement compared with horizontal head movement with neck flexion (Table 9.11).

Postural sway parameter	Head condition	Horizontal head movement		
		Extension	Neutral	Flexion
Sx (mm)	Static	1.10 ± 0.48	1.17 ± 0.53 **	1.23 ± 0.46 **
	0.2 m/s	1.64 ± 0.62	1.54 ± 0.76	1.55 ± 0.56
	1.0 m/s	1.97 ± 0.98	1.66 ± 0.64 *	1.64 ± 0.58 **
Sr (mm)	Static	0.56 ± 0.27	0.59 ± 0.30 **	0.61 ± 0.25 **
	0.2 m/s	0.82 ± 0.32	0.78 ± 0.41	0.77 ± 0.29
	1.0 m/s	0.99 ± 0.51	0.81 ± 0.32 *	0.82 ± 0.31 *
Sl (mm)	Static	0.54 ± 0.22	0.57 ± 0.24 *	0.61 ± 0.23 **
	0.2 m/s	0.82 ± 0.31	0.76 ± 0.36	0.78 ± 0.29
	1.0 m/s	0.98 ± 0.48	0.85 ± 0.36 *	0.82 ± 0.29 **

* $p<0.05$, ** $p<0.01$ significantly greater or less than extension.

Postural sway parameter	Head condition	Vertical head movement		
		Left	Looking ahead	Right
Sx (mm)	Static	1.13 ± 0.40	1.16 ± 0.53	1.20 ± 0.60
	0.2 m/s	1.59 ± 0.57	1.48 ± 0.54	1.59 ± 0.50
	1.0 m/s	1.78 ± 0.54	1.66 ± 0.50	1.77 ± 0.55
Sr (mm)	Static	0.57 ± 0.20	0.58 ± 0.30	0.61 ± 0.37
	0.2 m/s	0.80 ± 0.31	0.75 ± 0.30	0.80 ± 0.28
	1.0 m/s	0.89 ± 0.28	0.82 ± 0.25	0.89 ± 0.29
Sl (mm)	Static	0.57 ± 0.20	0.57 ± 0.24	0.59 ± 0.24
	0.2 m/s	0.79 ± 0.28	0.73 ± 0.26	0.79 ± 0.24
	1.0 m/s	0.89 ± 0.28	0.84 ± 0.26	0.88 ± 0.28

Postural sway parameter	Head condition	Diagonal head movement	
		LE	RE
Sx (mm)	Static	1.16 ± 0.46	1.18 ± 0.54
	0.2 m/s	1.63 ± 0.53	1.59 ± 0.50
	1.0 m/s	1.69 ± 0.55	1.77 ± 0.55
Sr (mm)	Static	0.58 ± 0.26	0.61 ± 0.32
	0.2 m/s	0.82 ± 0.28	0.80 ± 0.28
	1.0 m/s	0.84 ± 0.29	0.89 ± 0.29
Sl (mm)	Static	0.58 ± 0.22	0.57 ± 0.22
	0.2 m/s	0.80 ± 0.27	0.79 ± 0.24
	1.0 m/s	0.85 ± 0.30	0.88 ± 0.28

Table 9.11 **The interaction between static/dynamic head condition and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal direction with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of mediolateral sway (Sx) (separately to the right (Sr) and left (Sl)) (mean ± SD).**

At the higher velocity (Table 9.11) a significant reduction in Sx, due to the decrease in Sr, for RE diagonal head movement compared with horizontal head movement with neck extension was observed. However, at the higher velocity there was a significant increase in Sx, Sr and Sl for LE diagonal head movement compared with horizontal head movement with neck flexion. No differences in Sx, Sr and Sl were observed for head movement diagonally compared with vertically at the static head condition or either velocity, except for Sl at the lower velocity when a significant increase was observed for LE diagonal head movement compared with vertical head movement with rotation either to the right or left.

As shown in Table 9.12 with horizontal head movement in the static head condition there was a significant ($p<0.01$) decrease in Sy, due to the significant ($p<0.01$) reduction in Sa, with neck extension compared with flexion. At the lower velocity there was a significant increase in Sy ($p<0.01$), Sa ($p<0.01$) and Sp with neck extension compared with neutral. In addition, there was a significant increase in Sy, Sa and Sp with extension compared with flexion. At the higher velocity there was a significant ($p<0.01$) increase in Sy, Sa and Sp with neck extension compared with flexion. Furthermore, a significant ($p<0.01$) increase in Sa with neck extension compared with neutral was also observed.

For vertical head movement (Table 9.12) no differences in Sy, Sa and Sp were observed for the static head condition or lower velocity of movement. In contrast, at the higher velocity there was a significant ($p<0.01$) decrease in Sy, Sa and Sp with rotation to the right or left compared with looking directly ahead.

With diagonal head movements no differences in Sy, Sa and Sp were observed for the static head condition or for either velocity (Table 9.12). However, for the static head condition there was a significant decrease in Sy ($p<0.01$), Sa ($p<0.01$) and Sp for LE diagonal head movement compared with horizontal head movement with neck flexion.

Postural sway parameter	Head condition	Horizontal head movement		
		Extension	Neutral	Flexion
Sy (mm)	Static	0.88 ± 0.33	0.92 ± 0.33	0.95 ± 0.30 **
	0.2 m/s	1.36 ± 0.56	1.16 ± 0.47 **	1.22 ± 0.51 *
	1.0 m/s	1.48 ± 0.53	1.33 ± 0.75	1.28 ± 0.46 **
Sa (mm)	Static	0.43 ± 0.16	0.45 ± 0.16	0.48 ± 0.16 **
	0.2 m/s	0.67 ± 0.28	0.57 ± 0.23 **	0.61 ± 0.26 *
	1.0 m/s	0.74 ± 0.27	0.64 ± 0.25 **	0.64 ± 0.24 **
Sp (mm)	Static	0.45 ± 0.18	0.47 ± 0.18	0.47 ± 0.15
	0.2 m/s	0.68 ± 0.30	0.58 ± 0.27 *	0.61 ± 0.27 *
	1.0 m/s	0.74 ± 0.27	0.69 ± 0.63	0.64 ± 0.24 **

* p<0.05, ** p<0.01 significantly greater or less than extension.

Postural sway parameter	Head condition	Vertical head movement		
		Left	Looking ahead	Right
Sy (mm)	Static	0.89 ± 0.26	0.92 ± 0.33	0.92 ± 0.41
	0.2 m/s	1.31 ± 0.44	1.34 ± 0.42	1.41 ± 0.55
	1.0 m/s	1.72 ± 0.52 **	2.09 ± 0.59	1.75 ± 0.54 **
Sa (mm)	Static	0.44 ± 0.13	0.45 ± 0.16	0.46 ± 0.20
	0.2 m/s	0.67 ± 0.24	0.67 ± 0.23	0.69 ± 0.26
	1.0 m/s	0.86 ± 0.27 **	1.08 ± 0.33	0.89 ± 0.28 **
Sp (mm)	Static	0.46 ± 0.14	0.47 ± 0.17	0.46 ± 0.23
	0.2 m/s	0.64 ± 0.22	0.67 ± 0.21	0.71 ± 0.30
	1.0 m/s	0.85 ± 0.27 **	1.01 ± 0.27	0.86 ± 0.27 **

** significantly (p<0.01) less than looking directly ahead.

Postural sway parameter	Head condition	Diagonal head movement	
		LE	RE
Sy (mm)	Static	0.89 ± 0.31	0.92 ± 0.34
	0.2 m/s	1.52 ± 0.59	1.40 ± 0.51
	1.0 m/s	1.80 ± 0.61	1.64 ± 0.57
Sa (mm)	Static	0.44 ± 0.15	0.45 ± 0.16
	0.2 m/s	0.75 ± 0.30	0.68 ± 0.25
	1.0 m/s	0.90 ± 0.32	0.83 ± 0.31
Sp (mm)	Static	0.45 ± 0.16	0.47 ± 0.18
	0.2 m/s	0.77 ± 0.31	0.71 ± 0.28
	1.0 m/s	0.90 ± 0.30	0.81 ± 0.27

Table 9.12 **The interaction between static/dynamic head condition and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal direction with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)) (mean ± SD).**

At the lower velocity (Table 9.12) a significant increase in Sy, Sa and Sp was observed for both diagonal head movements (LE: $p<0.01$) compared with horizontal head movement with neck flexion. Similarly, at the higher velocity there was a significant ($p<0.01$) increase in Sy, Sa and Sp for both diagonal head movements compared with horizontal head movement with neck flexion. In addition, at the higher velocity a significant ($p<0.01$) increase in Sy, Sa and Sp for LE diagonal head movement compared with horizontal head movement with neck extension was observed. No differences in Sy, Sa and Sp were observed for diagonal head movement compared with vertical movements for the static head condition and the higher velocity of movement. In contrast, at the lower velocity there was a significant increase in Sy ($p<0.01$), Sa and Sp ($p<0.01$) for LE diagonal head movement compared with vertical head movement with rotation to the left.

There were no differences in TL, TLx and TLy for horizontal head movement in the static head condition (Table 9.13). However, at the lower velocity there was a significant increase in TL with neck extension compared with neutral, the increase being due to the significant ($p<0.01$) increase in TLy. There were also significant increases in TL, TLx and TLy with neck extension compared with flexion. At the higher velocity there were significant increases in TL ($p<0.01$), TLx and TLy ($p<0.01$) with neck extension compared with neutral. In addition, there was a significant increase TL ($p<0.01$), TLx ($p<0.01$) and TLy with neck extension compared with flexion.

As shown in Table 9.13 with vertical head movement in the static head condition no differences in TL, TLx and Tly were observed. At the lower velocity there was a significant ($p<0.01$) increase in TL with rotation to the right compared with looking directly ahead, the increase being due to the significant ($p<0.01$) increase in TLx. At the higher velocity there was a significant decrease in TL with rotation to the left compared with looking directly ahead, the decrease being due to the significant ($p<0.01$) reduction in TLy.

Postural sway parameter	Head condition	Horizontal head movement		
		Extension	Neutral	Flexion
TL (mm)	Static	173.0 ± 127.3	176.3 ± 110.3	172.3 ± 97.2
	0.2 m/s	221.9 ± 115.7	205.5 ± 120.8 *	206.3 ± 106.6 *
	1.0 m/s	247.3 ± 116.9	219.7 ± 107.2 **	218.5 ± 106.2 **
TLx (mm)	Static	98.6 ± 75.7	102.1 ± 67.8	98.2 ± 51.2
	0.2 m/s	130.6 ± 67.1	125.6 ± 74.8	121.8 ± 59.9 *
	1.0 m/s	151.6 ± 71.6	134.9 ± 64.4 *	129.7 ± 63.4 **
TLy (mm)	Static	106.3 ± 86.0	106.7 ± 70.2	105.6 ± 70.0
	0.2 m/s	137.3 ± 83.5	121.3 ± 80.0 **	126.2 ± 78.4 *
	1.0 m/s	149.0 ± 83.3	129.6 ± 75.7 **	133.6 ± 77.1 *

* $p<0.05$, ** $p<0.01$ significantly less than extension.

Postural sway parameter	Head condition	Vertical head movement		
		Left	Looking ahead	Right
TL (mm)	Static	166.9 ± 87.5	167.1 ± 93.3	187.6 ± 172.5
	0.2 m/s	211.2 ± 98.5	214.8 ± 111.9	224.2 ± 113.3 **
	1.0 m/s	241.9 ± 105.1 *	257.5 ± 108.2	250.1 ± 111.3
TLx (mm)	Static	92.6 ± 46.5	94.1 ± 51.8	112.2 ± 109.8
	0.2 m/s	124.8 ± 57.2	121.0 ± 65.3	131.0 ± 67.5 **
	1.0 m/s	138.5 ± 61.5	134.6 ± 68.4	142.2 ± 62.8
TLy (mm)	Static	103.7 ± 64.5	103.4 ± 66.8	111.5 ± 107.5
	0.2 m/s	130.0 ± 70.4	136.9 ± 81.0	139.9 ± 81.1
	1.0 m/s	154.9 ± 76.7 **	177.9 ± 75.2	162.1 ± 82.7

* $p<0.05$, ** $p<0.01$ significantly greater or less than looking directly ahead.

Postural sway parameter	Head condition	Diagonal head movement	
		LE	RE
TL (mm)	Static	170.1 ± 102.7	178.0 ± 121.4
	0.2 m/s	238.4 ± 122.7	223.9 ± 110.0
	1.0 m/s	257.0 ± 107.5	246.6 ± 118.1
TLx (mm)	Static	96.9 ± 57.5	103.3 ± 71.4
	0.2 m/s	140.5 ± 75.8	130.0 ± 63.3
	1.0 m/s	146.5 ± 59.6	141.2 ± 67.8
TLy (mm)	Static	104.3 ± 71.9	107.7 ± 80.2
	0.2 m/s	147.5 ± 82.7	140.6 ± 82.7
	1.0 m/s	165.9 ± 82.3	158.5 ± 89.4

Table 9.13 **The interaction between static/dynamic head condition and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the total path length (TL) and path length in the mediolateral (TLx) and anteroposterior (TLy) directions (mean ± SD).**

With diagonal head movement there were no differences in TL, TLx or TLy for the static head condition or either velocity of head movement (Table 9.13). No differences in TL, TLx and TLy were observed for diagonal head movements compared with horizontal or vertical head movement for the static head condition. However, at the lower velocity of movement there was a significant increase in TL, due to the significant ($p<0.01$) increase in TLy, for RE diagonal head movement and a significant ($p<0.01$) increase in TL, due to the significant ($p<0.01$) increase in TLx and TLy, for LE diagonal head movement compared with horizontal head movement with neck flexion. In addition, a significant ($p<0.01$) increase in TL, TLx and TLy was observed for LE diagonal head movement compared with vertical head movement with rotation to the left. At the higher velocity there were significant increases in TL ($p<0.01$), TLx and TLy ($p<0.01$) for both diagonal head movements compared with horizontal head movement with neck flexion. No differences in TL, TLx and TLy were observed between head movement diagonally and vertically at the higher velocity of movement.

The differences observed for Vm, Vxm and Vym were similar to those for TL, TLx and TLy (Table 9.14).

With horizontal head movement there was no significant difference in Ay for the static head condition or either velocity of movement (Table 9.15). With vertical head movement there was a significant decrease in Ay with rotation to the right compared with looking directly ahead. No differences in Ay were observed with vertical head movement at either velocity. For diagonal head movement there was no differences in Ay for the static head condition or either velocity of head movement (Table 9.15). For the static head condition there was a significant increase in Ay for LE diagonal head movement compared with horizontal head movement with neck flexion. In contrast, at the lower and higher velocities a significant decrease in Ay was observed for LE diagonal head movement compared with horizontal head movement with neck flexion. There was also a significant increase in Ay for both diagonal head movements for the static head condition compared with vertical head movement with rotation to the right. No differences in Ay were observed between head movement diagonally and vertically at either velocity.

Postural sway parameter	Head condition	Horizontal head movement		
		Extension	Neutral	Flexion
Vm (mm/s)	Static	8.68 ± 6.39	8.84 ± 5.53	8.64 ± 4.88
	0.2 m/s	11.1 ± 5.80	10.3 ± 6.06 *	10.4 ± 5.35 *
	1.0 m/s	12.4 ± 5.87	11.0 ± 5.38 **	11.0 ± 5.33 **
Vxm (mm/s)	Static	4.99 ± 3.76	5.12 ± 3.40	4.93 ± 2.57
	0.2 m/s	6.55 ± 3.37	6.30 ± 3.75	6.11 ± 3.00 *
	1.0 m/s	7.61 ± 3.59	6.77 ± 3.23 *	6.51 ± 3.18 **
Vym (mm/s)	Static	5.33 ± 4.32	5.36 ± 3.52	5.30 ± 3.51
	0.2 m/s	6.89 ± 4.19	6.08 ± 4.01 **	6.33 ± 3.94 *
	1.0 m/s	7.48 ± 4.18	6.50 ± 3.80 **	6.71 ± 3.87 *

* $p<0.05$, ** $p<0.01$ significantly less than extension.

Postural sway parameter	Head condition	Vertical head movement		
		Left	Looking ahead	Right
Vm (mm/s)	Static	8.37 ± 4.39	8.38 ± 4.68	9.41 ± 8.66
	0.2 m/s	10.6 ± 4.94	10.8 ± 5.62	11.2 ± 5.68 **
	1.0 m/s	12.1 ± 5.27 *	12.9 ± 5.43	12.6 ± 5.58
Vxm (mm/s)	Static	4.69 ± 2.27	4.72 ± 2.60	5.63 ± 5.51
	0.2 m/s	6.26 ± 2.87	6.07 ± 3.28	6.57 ± 3.39 **
	1.0 m/s	6.95 ± 3.09	6.75 ± 3.43	7.13 ± 3.15
Vym (mm/s)	Static	5.20 ± 3.24	5.19 ± 3.35	5.59 ± 5.40
	0.2 m/s	6.53 ± 3.53	6.87 ± 4.07	7.02 ± 4.07
	1.0 m/s	7.77 ± 3.85 *	8.93 ± 3.77	8.14 ± 4.15

* $p<0.05$, ** $p<0.01$ significantly greater or less than looking directly ahead.

Postural sway parameter	Head condition	Diagonal head movement	
		LE	RE
Vm (mm/s)	Static	8.54 ± 5.15	8.93 ± 6.09
	0.2 m/s	12.0 ± 6.16	11.2 ± 5.52
	1.0 m/s	12.9 ± 5.39	12.4 ± 5.93
Vxm (mm/s)	Static	4.86 ± 2.88	5.18 ± 3.58
	0.2 m/s	7.05 ± 3.80	6.52 ± 3.18
	1.0 m/s	7.35 ± 2.99	7.08 ± 3.40
Vym (mm/s)	Static	5.23 ± 3.61	5.40 ± 4.03
	0.2 m/s	7.40 ± 4.15	7.05 ± 4.15
	1.0 m/s	8.33 ± 4.13	7.95 ± 4.49

Table 9.14 **The interaction between static/dynamic head condition and horizontal head movement with the neck extended, in neutral and flexed, vertical direction with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the mean velocity of sway (Vm) and mean sway velocity in the mediolateral (Vxm) and anteroposterior (Vym) directions (mean ± SD).**

Postural sway parameter	Head condition	Horizontal head movement		
		Extension	Neutral	Flexion
Ay (^{0})	Static	-17.8 ± 48.8	-14.9 ± 46.3	-15.3 ± 46.2
	0.2 m/s	-17.6 ± 37.9	-14.8 ± 40.1	-18.9 ± 37.3
	1.0 m/s	-14.1 ± 33.8	-15.4 ± 36.8	-17.6 ± 36.7

Postural sway parameter	Head condition	Vertical head movement		
		Left	Looking ahead	Right
Ay (^{0})	Static	-18.3 ± 46.2	-18.8 ± 48.9	-10.9 ± 50.3 *
	0.2 m/s	-14.0 ± 36.9	-17.8 ± 34.3	-12.8 ± 36.8
	1.0 m/s	-9.79 ± 31.0	-12.2 ± 26.3	-13.0 ± 30.4

* significantly (p<0.05) less than looking directly ahead.

Postural sway parameter	Head condition	Diagonal head movement	
		LE	RE
Ay (^{0})	Static	-17.3 ± 47.4	-16.5 ± 46.1
	0.2 m/s	-8.87 ± 35.7	-13.8 ± 37.7
	1.0 m/s	-9.76 ± 30.4	-13.2 ± 34.9

Table 9.15 The interaction between static/dynamic head condition and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the angle of sway from the sagittal plane (Ay) (mean ± SD).

Interaction between sound, static/dynamic head condition and direction of head movement

The analyses of variance showed significant interactions between sound, static/dynamic head condition and direction of head movement for TL, TLx, TLy, Vm, Vxm, Vym and Ay.

No differences in TL, TLx and TLy in the static head condition or at 1595Hz and 2916Hz were observed. There were also no differences for diagonal head movement compared with that horizontally or vertically.

As shown in Table 9.16 with horizontal head movement at the lower velocity and frequency 1595Hz there was a significant increase in TL (p<0.01), TLx and TLy ($p<0.01$) with neck extension compared with flexion. There were no differences in TL, TLx and TLy with vertical or diagonal head movement at the lower velocity and frequency 1595Hz. There was a significant increase in TL, due to the significant increase in TLy, for LE diagonal head movement and a significant increase in TLy for RE diagonal head movement compared with horizontal head movement with neck flexion. No differences in TL, TLx and TLy were observed between diagonal and vertical head movements.

At 2916Hz with horizontal head movement at the lower velocity (Table 9.16) there was a significant increase in TL with neck extension compared with neutral, due to the significant ($p<0.01$) increase in TLy. For vertical head movement there was a significant increase in TL with rotation to the right compared with looking directly ahead, this being due to the significant increase in TLx. Furthermore, there was a significant ($p<0.01$) increase in TL, TLx and TLy with rotation to the right compared with rotation to the left. No differences in TL, TLx and TLy were observed at the lower velocity for diagonal head movement at 2916Hz. A significant ($p<0.01$) increase was observed in TL, due to the significant ($p<0.01$) increase in both TLx and TLy, for LE diagonal head movement and a significant increase in TL, due to the significant increase in TLy, for RE diagonal head movement compared with horizontal head movement with neck flexion. In addition, a significant ($p<0.01$) increase in TL, due to the significant ($p<0.01$) increase in TLy for LE diagonal head movement compared with horizontal head movement with neck extension was also observed. There was a significant ($p<0.01$) increase in TL, TLx and TLy for LE diagonal head movement compared with vertical head movement with rotation to the left.

As shown in Table 9.17 at the higher velocity of head movement at 1595Hz there was a significant increase in TL, TLx and TLy with neck extension compared with flexion for horizontal head movement. For vertical head movement there was a significant ($p<0.01$) increase in TL with rotation to the left compared with looking directly ahead, being due to the significant ($p<0.01$) increase in TLy. In addition, there was significant ($p<0.01$) increase TLy with rotation to the right compared with looking directly ahead. No differences in TL, TLx or TLy were observed for diagonal head movement at the higher velocity at 1595Hz. There was a significant ($p<0.01$) increase in TL, due to the significant ($p<0.01$) increase in TLy, for both diagonal head movements compared with horizontal head movement with neck flexion. No differences in TL, TLx or TLy were observed between head movements diagonally and vertically.

Postural sway parameter	Frequency	Horizontal head movement		
		Extension	Neutral	Flexion
TL (mm)	1595 Hz	231.7 ± 127.4	213.8 ± 131.8	208.7 ± 113.3 **
	2916 Hz	212.0 ± 103.8	197.2 ± 110.2 *	203.8 ± 101.3
TLx (mm)	1595 Hz	135.6 ± 72.9	133.0 ± 83.6	123.9 ± 62.2 *
	2916 Hz	125.5 ± 61.7	118.2 ± 65.5	119.6 ± 58.4
TLy (mm)	1595 Hz	144.1 ± 90.8	127.3 ± 82.8	123.9 ± 85.0 **
	2916 Hz	130.5 ± 76.5	118.6 ± 76.0 **	125.1 ± 75.2

* $p<0.05$, ** $p<0.01$ significantly less than extension.

Postural sway parameter	Frequency	Vertical head movement		
		Left	Looking ahead	Right
TL (mm)	1595 Hz	218.4 ± 93.1	215.1 ± 119.4	218.9 ± 110.7
	2916 Hz	204.1 ± 104.8 **	214.6 ± 106.0 *	229.5 ± 117.4
TLx (mm)	1595 Hz	131.1 ± 55.8	118.2 ± 69.7	125.4 ± 64.8
	2916 Hz	118.6 ± 58.8 **	123.8 ± 61.7 *	136.6 ± 70.7
TLy (mm)	1595 Hz	133.2 ± 65.3	140.1 ± 85.9	138.5 ± 81.9
	2916 Hz	126.9 ± 76.2 **	133.6 ± 77.2	141.2 ± 81.6

* $p<0.05$, ** $p<0.01$ significantly less than rotation to the right.

Postural sway parameter	Frequency	Diagonal head movement	
		LE	RE
TL (mm)	1595 Hz	235.0 ± 118.8	229.1 ± 109.1
	2916 Hz	241.7 ± 128.4	218.7 ± 112.6
TLx (mm)	1595 Hz	137.5 ± 76.0	134.8 ± 63.6
	2916 Hz	143.6 ± 76.7	125.2 ± 63.7
TLy (mm)	1595 Hz	146.0 ± 77.4	142.0 ± 81.1
	2916 Hz	149.1 ± 89.0	139.1 ± 85.8

Table 9.16 **The interaction between sound, head movement at 0.2m/s and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the total path length (TL) and path length in the mediolateral (TLx) and anteroposterior (TLy) directions (mean ± SD).**

Postural sway parameter	Frequency	Horizontal head movement		
		Extension	Neutral	Flexion
TL (mm)	1595 Hz	241.9 ± 113.1	234.8 ± 123.8	219.2 ± 106.9 *
	2916 Hz	252.7 ± 122.2	204.6 ± 87.1 **	217.8 ± 107.4 *
TLx (mm)	1595 Hz	147.2 ± 66.3	146.1 ± 74.0	131.1 ± 63.0 *
	2916 Hz	155.9 ± 77.4	123.8 ± 51.9 **	128.2 ± 64.9 **
TLy (mm)	1595 Hz	146.5 ± 83.4	137.8 ± 86.7	133.2 ± 78.2 *
	2916 Hz	151.5 ± 84.6	121.4 ± 63.2 **	134.0 ± 77.3 *

* p<0.05, ** p<0.01 significantly less than extension.

Postural sway parameter	Frequency	Vertical head movement		
		Left	Looking ahead	Right
TL (mm)	1595 Hz	240.7 ± 103.2 **	260.7 ± 114.0	249.2 ± 112.0
	2916 Hz	243.2 ± 108.6	254.3 ± 104.0	251.0 ± 112.4
TLx (mm)	1595 Hz	137.4 ± 58.1	133.4 ± 65.7	140.1 ± 60.7
	2916 Hz	139.7 ± 65.7	135.8 ± 72.2	144.2 ± 65.8
TLy (mm)	1595 Hz	154.1 ± 76.9 **	183.2 ± 83.6	162.9 ± 85.5 **
	2916 Hz	155.8 ± 77.8	172.6 ± 66.7	161.4 ± 81.4

** significantly (p<0.01) less than looking directly ahead.

Postural sway parameter	Frequency	Diagonal head movement	
		LE	RE
TL (mm)	1595 Hz	258.0 ± 109.5	246.5 ± 116.4
	2916 Hz	255.9 ± 107.2	246.8 ± 121.9
TLx (mm)	1595 Hz	147.8 ± 58.8	141.9 ± 66.3
	2916 Hz	145.2 ± 61.4	140.4 ± 70.5
TLy (mm)	1595 Hz	166.2 ± 82.9	157.0 ± 88.6
	2916 Hz	165.7 ± 83.1	159.9 ± 91.8

Table 9.17 **The interaction between sound, head movement at 1.0m/s and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal direction with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the total path length (TL) and path length in the mediolateral (TLx) and anteroposterior (TLy) directions (mean ± SD).**

At 2916Hz with horizontal head movement at the higher velocity of movement (Table 9.17) there was a significant increase in TL, TLx (p<0.01) and TLy with neck extension compared with flexion. In addition, there was a significant (p<0.01) increase in TL, TLx and TLy with neck extension compared with neutral. No differences were observed for vertical or diagonal head movement. There was a significant ($p<0.01$) increase in TL, due to the significant ($p<0.01$) increase in TLy, for both diagonal head movements compared with horizontal head movement with neck flexion. No differences in TL, TLx or TLy were observed between head movements diagonally and vertically.

No differences in Vm, Vxm or Vym were observed at the static head condition at either sound frequency for any head movement, as well as between head movement diagonally and horizontally or vertically. At both velocities of head movement at either frequency the observations with respect to Vm, Vxm and Vym (Table 9.18 and 9.19) correspond to those for TL, TLx and TLy.

As shown in Table 9.20 for the static head condition at 1595Hz there was a significant increase in Ay with neck extension compared with neutral for horizontal head movement. However, for vertical head movement there was a significant decrease in Ay with rotation to the right compared with looking directly ahead and rotation to the left. There were no differences in Ay for diagonal head movement. No differences were observed between head movement diagonally and horizontally. There was a significant increase in Ay for both diagonal head movements (LE: $p<0.01$) compared with vertical head movement with rotation to right. At 2916Hz for the static head condition there were no differences in Ay with any direction of head movement, as well as between head movement diagonally and horizontally or vertically.

For the two velocities of movement at either 1595Hz or 2916Hz there were no differences in Ay for any direction of head movement. However, at the lower velocity at 2916Hz there was a significant decrease in Ay for LE diagonal head movement compared with head movement horizontally with neck extension or flexion. At the higher velocity at 2916Hz there was a significant ($p<0.01$) decrease in Ay for LE diagonal head movement compared with head movement horizontally with neck flexion.

Postural sway parameter	Frequency	Horizontal head movement		
		Extension	Neutral	Flexion
Vm (mm/s)	1595 Hz	11.6 ± 6.40	10.7 ± 6.61	10.5 ± 5.69 **
	2916 Hz	10.6 ± 5.21	9.89 ± 5.53 *	10.2 ± 5.08
Vxm (mm/s)	1595 Hz	6.81 ± 3.66	6.67 ± 4.19	6.22 ± 3.12 *
	2916 Hz	6.30 ± 3.10	5.93 ± 3.29	6.00 ± 2.93
Vym (mm/s)	1595 Hz	7.23 ± 4.55	6.39 ± 4.16	6.22 ± 4.26 **
	2916 Hz	6.55 ± 3.84	6.28 ± 3.77 **	5.95 ± 3.81

* $p<0.05$, ** $p< 0.01$ significantly less than extension.

Postural sway parameter	Frequency	Vertical head movement		
		Left	Looking ahead	Right
Vm (mm/s)	1595 Hz	11.0 ± 4.67	10.8 ± 5.99	11.0 ± 5.56
	2916 Hz	10.2 ± 5.26 **	10.8 ± 5.32 *	11.5 ± 5.89
Vxm (mm/s)	1595 Hz	6.58 ± 2.80	5.93 ± 3.50	6.29 ± 3.25
	2916 Hz	5.95 ± 2.95 **	6.21 ± 3.10 *	6.85 ± 3.55
Vym (mm/s)	1595 Hz	6.68 ± 3.28	7.03 ± 4.31	6.95 ± 4.11
	2916 Hz	6.37 ± 3.82 **	6.70 ± 3.87	7.09 ± 4.09

* $p<0.05$, ** $p<0.01$ significantly less than rotation to the right.

Postural sway parameter	Frequency	Diagonal head movement	
		LE	RE
Vm (mm/s)	1595 Hz	11.8 ± 5.96	11.5 ± 5.47
	2916 Hz	12.1 ± 6.44	11.0 ± 5.65
Vxm (mm/s)	1595 Hz	6.90 ± 3.81	6.77 ± 3.19
	2916 Hz	7.20 ± 3.85	6.28 ± 3.19
Vym (mm/s)	1595 Hz	7.33 ± 3.88	7.12 ± 4.07
	2916 Hz	7.48 ± 4.46	6.98 ± 4.30

Table 9.18 **The interaction between sound, head movement at 0.2m/s and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the mean velocity of sway (Vm) and mean sway velocity in the mediolateral (Vxm) and anteroposterior (Vym) directions (mean ± SD).**

Postural sway parameter	Frequency	Horizontal head movement		
		Extension	Neutral	Flexion
Vm (mm/s)	1595 Hz	12.1 ± 5.68	11.8 ± 6.21	11.0 ± 5.36 *
	2916 Hz	12.7 ± 6.13	10.3 ± 4.37 **	10.9 ± 5.39 *
Vxm (mm/s)	1595 Hz	7.39 ± 3.33	7.33 ± 3.72	6.58 ± 3.16 *
	2916 Hz	7.82 ± 3.88	6.21 ± 2.60 **	6.43 ± 3.26 **
Vym (mm/s)	1595 Hz	7.35 ± 4.19	6.92 ± 4.35	6.68 ± 3.92 *
	2916 Hz	7.60 ± 4.24	6.09 ± 3.17 **	6.73 ± 3.88 *

* $p<0.05$, ** $p<0.01$ significantly less than extension.

Postural sway parameter	Frequency	Vertical head movement		
		Left	Looking ahead	Right
Vm (mm/s)	1595 Hz	12.1 ± 5.18 **	13.1 ± 5.72	12.5 ± 5.62
	2916 Hz	12.2 ± 5.45	12.8 ± 5.22	12.6 ± 5.64
Vxm (mm/s)	1595 Hz	6.89 ± 2.92	6.69 ± 3.30	7.03 ± 3.05
	2916 Hz	7.01 ± 3.30	6.81 ± 3.62	7.24 ± 3.30
Vym (mm/s)	1595 Hz	7.73 ± 3.86 **	9.19 ± 4.20	8.17 ± 4.29 **
	2916 Hz	7.82 ± 3.91	8.66 ± 3.35	8.10 ± 4.08

** significantly ($p<0.01$) less than looking directly ahead.

Postural sway parameter	Frequency	Diagonal head movement	
		LE	RE
Vm (mm/s)	1595 Hz	12.9 ± 5.49	12.4 ± 5.84
	2916 Hz	12.8 ± 5.38	12.4 ± 6.11
Vxm (mm/s)	1595 Hz	7.42 ± 2.95	7.12 ± 3.33
	2916 Hz	7.29 ± 3.08	7.05 ± 3.54
Vym (mm/s)	1595 Hz	8.34 ± 4.16	7.88 ± 4.45
	2916 Hz	8.31 ± 4.17	8.02 ± 4.60

Table 9.19 The interaction between sound, head movement at 1.0m/s and horizontal head movement with the neck extended, in neutral and flexed, vertical direction with rotation to the left, looking directly ahead and rotation to the right and diagonal direction with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the mean velocity of sway (Vm) and mean sway velocity in the mediolateral (Vxm) and anteroposterior (Vym) directions (mean ± SD).

Postural sway parameter	Frequency	Horizontal head movement		
		Extension	Neutral	Flexion
Static head				
Ay (^{0})	1595 Hz	-18.3 ± 53.8 *	-14.4 ± 51.2	-15.7 ± 51.1
	2916 Hz	-17.3 ± 44.2	-15.4 ± 41.7	-14.9 ± 41.6
0.2 m/s				
Ay (^{0})	1595 Hz	-15.4 ± 36.5	-10.7 ± 39.4	-20.5 ± 37.9
	2916 Hz	-19.8 ± 39.7	-18.9 ± 41.0	-17.3 ± 37.3
1.0 m/s				
Ay (^{0})	1595 Hz	-14.6 ± 33.7	-12.9 ± 36.6	-16.8 ± 35.8
	2916 Hz	-13.7 ± 34.4	-17.9 ± 37.5	-18.3 ± 38.3

* significantly ($p<0.05$) greater than neutral.

Postural sway parameter	Frequency	Vertical head movement		
		Left	Looking ahead	Right
Static head				
Ay (^{0})	1595 Hz	-20.8 ± 51.6	-20.0 ± 53.2	-7.61 ± 55.5 *
	2916 Hz	-15.7 ± 40.8	-17.6 ± 45.2	-14.2 ± 45.2
0.2 m/s				
Ay (^{0})	1595 Hz	-12.4 ± 35.7	-18.6 ± 35.4	-15.1 ± 35.6
	2916 Hz	-15.7 ± 38.6	-17.0 ± 33.7	-10.5 ± 38.4
1.0 m/s				
Ay (^{0})	1595 Hz	-8.9 ± 30.9	-14.2 ± 28.4	-14.2 ± 30.4
	2916 Hz	-10.7 ± 31.6	-10.3 ± 24.2	-11.8 ± 30.9

* significantly ($p<0.05$) less than looking directly ahead and rotation to the left.

Postural sway parameter	Frequency	Diagonal head movement	
		LE	RE
Static head			
Ay (^{0})	1595 Hz	-17.9 ± 52.5	-15.5 ± 50.5
	2916 Hz	-16.8 ± 42.6	-17.5 ± 42.1
0.2 m/s			
Ay (^{0})	1595 Hz	-10.4 ± 36.9	-15.4 ± 39.7
	2916 Hz	-7.37 ± 35.1	-12.3 ± 36.3
1.0 m/s			
Ay (^{0})	1595 Hz	-11.7 ± 30.7	-11.3 ± 34.7
	2916 Hz	-7.81 ± 30.5	-15.2 ± 35.5

Table 9.20 **The interaction between sound, static/dynamic head condition and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the angle of sway from the sagittal plane (Ay) (mean ± SD).**

9.4 Discussion

The COG projection in the mediolateral direction appears to be influenced by sex, with females being influenced to a greater extent than males. The visual system is necessary to stabilise a stationary or moving object (Fleming et al. 1969) and is important in lateral sway control (Kollegger et al. 1989). Furthermore, the visual system has been found to be more important in males than females for all age groups (Kollegger et al. 1992). Thus, under this experimental condition it is possible that males were able to control movement of the COG projection in the mediolateral direction better than females.

Movement of the head stimulates the vestibular system (Carpenter 1990; Pansky et al. 1992) as well as the neck proprioceptors (Abrahams 1977). The results from the various velocities of movement indicate that both the vestibular and neck proprioceptor systems are dependent on the velocity of head movement. These two systems control the magnitude of sway, total path length and mean velocity of sway in both the mediolateral and anteroposterior directions. Galvanic vestibular stimulation (Inglis et al. 1995) and vibrostimulation of the neck muscles (Lund 1980) has been shown to decrease postural stability. It is suggested that stimulation of both systems leads to a disturbance of equilibrium resulting in increased postural sway.

During horizontal head movement neck extension has a more powerful effect in causing postural instability than does flexion or the neutral position. The decrease in postural stability induced by neck extension has been suggested as being due to the poor working position of the vestibular system (Jackson and Epstein 1991). The findings in this experiment also suggest that there is different stimulation of the vestibular system during neck extension and flexion. Changes in head position activate the otoliths leading to depolarisation of the hair cells during neck extension but hyperpolarising them during neck flexion (Livingston 1990; Sherwood 1997). Thus, depolarisation of the vestibular system is suggested to be the cause of the postural instability.

Vertical head movement induces increased postural instability in the mediolateral direction, but appears to improve stability in the anteroposterior direction. Vibration to one side of neck muscles causes postural sway to the side of the stimulation (Smetanin et al. 1993). It, therefore appears that dynamic asymmetrical neck proprioceptor input stabilises postural sway in the anteroposterior direction.

Diagonal head movement shows a greater postural instability than horizontal head movement with neck flexion or vertical head movement with rotation to the left. In addition, for anteroposterior sway diagonal head movement also causes greater sway than does horizontal head movement with neck extension. For the mediolateral direction the vestibular and neck proprioceptor inputs each increase in sway behaviour. In contrast, for the anteroposterior direction the vestibular input increases sway behaviour but neck proprioceptor input decreases it. It is, therefore suggested that the interaction between vestibular and neck proprioceptor input leads to postural destabilisation, with the vestibular input from neck extension appearing to be the primary destabilising factor. This interaction is additive, confirming the observation of Anastasopoulos and Mergner (1982) and Karnath et al. (1994) and depends on the vestibular input.

The interaction between sex and direction of head movement on the COG projection in the anteroposterior direction shows that for horizontal head movements female are less stable when the neck is extended or flexed, while for vertical head movement they are more stable when the neck is rotated to the right or left. It is postulated that vestibular and neck proprioceptor cues are important in females in controlling the COG projection in the anteroposterior direction. It is suggested that vestibular input destabilises the anteroposterior COG projection, while neck proprioceptor input stabilises it. In males, although there is no effect of either vestibular or neck proprioceptor input on the anteroposterior COG projection, there is an effect of the interaction between vestibular and neck proprioceptor input causing a posterior shift. It is suggested that in males such interaction influences only the anteroposterior COG projection leading to postural instability.

The interaction between sound and the direction of head movement appears to have an influence on sway magnitude in the mediolateral direction. The frequency 1595Hz has been report to have a stabilising effect while 2916Hz has a destabilising effect in sway behaviour (Sakellari and Soames 1996), sway increasing with flexion and extension of the neck. Thus, for horizontal head movement the interaction between vestibular and auditory inputs seems to have an integrating effect. In contrast, vertical head movements at 1595Hz with neck rotation leads to postural instability. The auditory input has been reported to have an influence on the mediolateral direction of sway (Sakellari and Soames 1996). It is, therefore, suggested that the interaction between neck proprioceptor and auditory input in the control of sway magnitude in the mediolateral direction is dependent on the auditory input. Diagonal head movement shows an interaction between the vestibular, neck proprioceptor and auditory systems. Such interaction causes postural instability in the mediolateral direction. It appears that at 1595Hz neck proprioception is a destabilising cue since no change is observed in mediolateral sway for the interaction between vestibular and auditory inputs. At 2916Hz the vestibular input appears to be the destabilising factor in the interaction between the vestibular, neck proprioceptor and auditory systems since neck rotation to the left at 2916Hz does not increase mediolateral sway. The destabilising effect of the vestibular system may be due to the disturbance of the vestibular receptors by the high frequency of the sound since noise has been reported to damage the receptors of the vestibulocochlear nerve causing an impairment of hearing and a degradation of balance (Kilburn et al. 1992).

The interaction between sex, sound and the direction of head movement showed a difference for horizontal head movements between females and males. The results reveal that for horizontal movements the interaction between auditory and vestibular input stabilises the mediolateral COG projection in males at the lower sound frequency. At the higher frequency the interaction depends on the vestibular input leading postural stability or instability. Thus, it is possible that this interaction is important in males in restricting movement the COG projection in the mediolateral direction.

The interaction between static/dynamic head condition and direction of head movement has an influence on most postural sway parameters. For the COG projection the interaction appears to be stronger in the anteroposterior direction. For horizontal head movement there is a difference between the static and dynamic head condition. In the static condition neck extension has no influence on the anteroposterior COG projection, path lengths, sway velocities or the angle of sway. However, during dynamic head movement there is a posterior shift of the COG projection, an increase in sway magnitude, path lengths and sway velocities, but no change in the angle of sway. This clearly indicates a differential influence of the vestibular input in these two conditions. Dynamic vestibular input, particularly with neck extension, causes postural instability. For vertical head movement it reveals that static neck proprioception influences the anteroposterior COG projection and the angle of sway. At the lower velocity dynamic neck proprioception destabilises posture by the increasing mediolateral path length, while at the higher velocity the interaction between vestibular and neck proprioceptor inputs leads to postural stability in the anteroposterior direction. For diagonal head movement there is an interaction between vestibular and neck proprioceptor inputs on sway behaviour. Dynamic vestibular input is the destabilising cue in this interaction leading to an increase in sway magnitude, path lengths and sway velocities. The interaction also appears to reduce the angle of sway.

The interaction between sound and static/dynamic head condition and the direction of head movement influences total path length and the mean velocity of sway in both the mediolateral and anteroposterior directions, as well as the angle of sway from the sagittal plane. The findings indicate that with horizontal movements the stabilising or destabilising effect of sound combines with the dynamic vestibular input causing postural instability, seen as an increase in the total path length and mean sway velocity. For vertical movement at the lower velocity the destabilising effect of sound combines with neck proprioceptor stimulation causing postural instability. The difference between neck rotation to the right and left may be due to handedness and/or one ear being dominant over the other. At the higher velocity the stabilising effect of sound combining with the vestibular and neck proprioceptor inputs leads to postural stability by decreasing anteroposterior path length and sway velocity. It is suggested that the stabilising effect of sound, vestibular and neck proprioceptor inputs has an additive effect on the anteroposterior path length and velocity of sway. For diagonal head movement the interaction between vestibular, neck proprioceptor and auditory inputs has an effect on path lengths and sway velocities. The increase in these sway behaviours with diagonal compared with horizontal head movement with neck flexion is possibly due to the vestibular input from neck extension.

For the angle of sway from the sagittal plane, the findings reveal that the velocity of head movement difference is dependent on the direction of head movement. Static vestibular and neck proprioceptor inputs combine with the stabilising effect of sound leading to a change in the angle of sway from the sagittal plane. For horizontal head movements the angle of sway from the sagittal plane is increased by the interaction between vestibular and auditory inputs, whereas for vertical movements it is reduced by the interaction between neck proprioceptor and auditory inputs. The interaction between vestibular, neck proprioceptor and auditory inputs appear to be additive leading to a reduction in the angle of sway.

9.5 Summary

There is difference in response to static and dynamic vestibular and neck proprioceptor stimulation on postural control in the presence of auditory stimulation. The response to static vestibular and neck proprioceptor stimulation leads to increases postural stability than does dynamic vestibular and neck proprioceptor stimulation. The vestibular input with neck extension causes postural instability. Neck proprioceptor input leads to postural destabilisation in the mediolateral direction but improves postural stability in the anteroposterior direction. The interaction between vestibular and neck proprioceptor inputs leads to postural stability in the anteroposterior direction and appears to depend on the vestibular input. The interaction between vestibular and auditory inputs has an integrating effect in the mediolateral direction, while the interaction between neck proprioceptor and auditory inputs depends on the auditory input in controlling sway in this direction. The interaction between vestibular, neck proprioceptor and the auditory systems increases mediolateral sway depending on the neck proprioceptor input at 1595Hz and vestibular input at 2916Hz. The interaction between dynamic vestibular and auditory, dynamic neck proprioceptor and auditory, as well as dynamic vestibular, neck proprioceptor and auditory input all influence path lengths, velocities of sway and the angle of sway.

Chapter 10

Responses to visual, auditory, static vestibular and neck proprioceptor stimulation

10.1 Introduction

Postural maintenance is influenced by vision (Gantchev et al. 1981; Paulus et al. 1984), vestibular (Keshner et al. 1987; Horak et al. 1990), neck proprioception (Manzoni et al. 1979; Dietz et al. 1988) and auditory input (Juntunen et al. 1987; Raper and Soames 1991; Kilburn et al. 1992; Soames and Raper 1992). It has been reported that the interaction between any two sensory system; visual-vestibular (Kolev et al. 1996; Brandt et al. 1998), visual-neck proprioception (Roll et al. 1991; Wolsley et al. 1996) and vestibular-neck proprioception (Mergner et al. 1991, 1992; Karnath et al. 1994) are sufficient to achieve successful postural control. However, the influence of visual-auditory, vestibular-auditory and neck proprioception-auditory interactions on postural balance are not well known. Some investigators (Takeya et al. 1976; Lueck et al. 1990; Sakellari and Soames 1996) have reported an interaction between vision and auditory input, while others (Rapers and Soames 1991; Soames and Rapers 1992) did not find such an interaction in postural control. In man, because of the lack of any observable interaction between vision-auditory, the vestibular-auditory interaction has been suggested not occur (Soames and Raper 1992). In addition, the interaction between any three sensory inputs has not been reported. The aim of this chapter is to investigate the individual and interaction of visual, auditory and static vestibular and neck proprioception on postural sway behaviour.

10.2 Materials and methods

Twenty one healthy subjects (12 females, 9 males), aged between 18 and 30 years, participated in the experiment.

A total 54 measurements; looking directly ahead (A), 45^0 neck rotation to the right (R) and left (L), each with the neck in neutral (N), 45^0 flexion (F) or extension (E) with the eyes open (O) and closed (C), and with no sound and auditory stimulation at 1595Hz and 2916Hz, were taken from each subject. The recordings of postural sway behaviour were taken with the subject standing comfortably erect with the feet together on the force platform after they had been instructed to look at and focus on a specific marker placed on the screen (for further details see Chapter 3 part 3.7.3).

Five-way analyses of variance were conducted on each of the sway parameters (Chapter 3 part 3.3) with sex, vision, neck rotation (looking ahead/right/left), neck flexion/extension (neutral/flexion/extension) and sound frequency as independent variables in order to determine the influence of each on postural sway behaviour. t-tests were conducted as appropriate to determine the significant differences for each independent variable influencing each postural sway parameter. In addition, t-tests were also conducted for subject characteristics. Unless otherwise stated all differences are at the 5% level of significance.

10.3 Results

10.3.1 Subject characteristics

The characteristics of the population studied are given in Table 10.1, with the data being presented for the whole group, as well as for females and males separately. There was no difference in age between females and males, however height, foot length and eye level height were all significantly ($p<0.01$) greater and eye-object distance significantly ($p<0.01$) smaller in males.

Subject characteristics	All	Females	Males
Age (year)	24.7 ± 4.29	25.8 ± 4.18	23.2 ± 4.24
Height (cm)	165.2 ± 10.9	159.0 ± 8.39	173.4 ± 7.94 **
Foot length (cm)	24.5 ± 1.78	23.6 ± 0.87	25.8 ± 1.90 **
Eye-Object distance (cm)	49.0 ± 1.78	49.9 ± 0.87	47.7 ± 1.90 **
Eye level height (cm)	154.8 ± 11.0	148.8 ± 8.41	162.9 ± 8.46 **

** significantly ($p<0.01$) greater or less than female value.

Table 10.1 The characteristics of the subjects (12 females, 9 males) who participated in Experiments 1 and 3 (mean ± SD).

10.3.2 Analyses of variance

The results of the various analyses of variance are presented in Appendix 11, showing the influence of sex, vision, sound, neck rotation and neck flexion/extension and their interactions on the various parameters of postural sway behaviour.

Sex

Few differences in sway behaviour were observed between females and males, the difference being restricted to X. There was a significant ($p<0.01$) shift in the COG projection to the right in females (3.98 ± 2.02) compared with males (2.07 ± 2.17).

Vision

As shown in Table 10.2 the loss of vision influenced most postural sway parameters. As can be seen the mean mediolateral (Sx, Sr, Sl) and anteroposterior (Sy, Sa, Sp) sway magnitudes were both significantly ($p<0.01$) increased when standing with eyes closed compared with eyes open. In addition, the total path length and the mean velocity of sway, including those in the mediolateral and anteroposterior directions were also significantly ($p<0.01$) increased without visual feedback. There was no difference in X, Y and Ay.

Postural sway parameter	Vision	
	Eyes open	Eyes closed
X (mm)	3.20 ± 2.27	3.12 ± 2.32
Y (mm)	0.95 ± 2.36	0.86 ± 2.33
Sx (mm)	1.00 ± 0.57	1.38 ± 0.66 **
Sr (mm)	0.50 ± 0.33	0.69 ± 0.34 **
Sl (mm)	0.49 ± 0.26	0.69 ± 0.35 **
Sy (mm)	0.77 ± 0.37	1.07 ± 0.49 **
Sa (mm)	0.38 ± 0.18	0.54 ± 0.28 **
Sp (mm)	0.39 ± 0.20	0.54 ± 0.24 **
TL (mm)	147.9 ± 127.7	177.2 ± 127.7 **
TLx (mm)	85.4 ± 79.4	104.2 ± 72.8 **
TLy (mm)	90.9 ± 82.0	110.0 ± 87.8 **
Vm (mm/s)	7.42 ± 6.41	8.89 ± 6.41 **
Vxm (mm/s)	4.30 ± 3.97	5.23 ± 3.66 **
Vym (mm/s)	4.56 ± 4.12	5.52 ± 4.41 **
Ay (°)	4.30 ± 50.8	5.66 ± 43.6

** significantly (p<0.01) greater than with eyes open.

Table 10.2 **The influence of vision on the centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions, magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), total path length (TL), mediolateral (TLx) and anteroposterior (TLy) path lengths, mean velocity of sway (Vm), mediolateral (Vxm) and anteroposterior (Vym) sway velocities, and angle of sway from the sagittal plane (Ay) (mean ± SD).**

Sound

As shown in Table 10.3 all postural sway parameters, except Ay, showed significantly (p<0.01) greater stability when standing without sound than with frequencies 1595Hz and 2916Hz. There was also a significant decrease in Sx (p<0.01), Sr and Sl (p<0.01) at 1595Hz compared with 2916Hz.

Neck rotation

Neck rotation had a significant influence on X, TLx and Vxm. As shown in Table 10.4 there was a significant (p<0.01) shift to the right and increase in TLx and Vxm with the neck rotated to the right compared with looking directly ahead or with rotation to the left.

Postural sway parameter	Frequency		
	No sound	1595 Hz	2916 Hz
X (mm)	2.13 ± 1.99 **	3.70 ± 2.67	3.65 ± 1.76
Y (mm)	2.16 ± 2.55 **	0.28 ± 1.94	0.28 ± 1.97
Sx (mm)	0.84 ± 0.35 **	1.31 ± 0.61 ++	1.42 ± 0.75
Sr (mm)	0.42 ± 0.18 **	0.66 ± 0.34 +	0.71 ± 0.41
Sl (mm)	0.42 ± 0.18 **	0.64 ± 0.30 ++	0.70 ± 0.38
Sy (mm)	0.67 ± 0.28 **	1.04 ± 0.47	1.06 ± 0.48
Sa (mm)	0.33 ± 0.14 **	0.51 ± 0.26	0.53 ± 0.27
Sp (mm)	0.34 ± 0.15 **	0.53 ± 0.24	0.53 ± 0.24
TL (mm)	91.3 ± 17.3 **	194.9 ± 150.8	201.6 ± 137.4
TLx (mm)	56.6 ± 11.7 **	112.3 ± 93.9	115.5 ± 80.8
TLy (mm)	57.2 ± 11.1 **	119.6 ± 99.4	124.7 ± 95.3
Vm (mm/s)	4.56 ± 0.87 **	9.78 ± 7.57	10.12 ± 6.90
Vxm (mm/s)	2.83 ± 0.58 **	5.64 ± 4.71	5.82 ± 4.03
Vym (mm/s)	2.85 ± 0.57 **	6.00 ± 4.99	6.26 ± 4.78
Ay (°)	33.0 ± 33.7 **	-10.2 ± 51.1	-7.86 ± 42.5

** significantly ($p<0.01$) greater or less than frequencies 1595Hz and 2916Hz.
+ $p<0.05$, ++ $p<0.01$ significantly less than frequency 2916Hz.

Table 10.3 **The influence of sound on the centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions, magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), total path length (TL), mediolateral (TLx) and anteroposterior (TLy) path lengths, mean velocity of sway (Vm), mediolateral (Vxm) and anteroposterior (Vym) sway velocities, and angle of sway from the sagittal plane (Ay) (mean ± SD).**

Postural sway parameter	Neck rotation		
	Left	Looking ahead	Right
X (mm)	3.04 ± 2.27	3.12 ± 2.32	3.32 ± 2.29 **
TLx (mm)	88.7 ± 48.9	90.7 ± 64.8	105.0 ± 104.6 **
Vxm (mm/s)	4.47 ± 2.42	4.55 ± 3.25	5.27 ± 5.25 **

** significantly ($p<0.01$) greater than looking directly ahead and rotation to the left.

Table 10.4 **The influence of neck rotation on the centre of gravity projection (X), path length (TLx) and sway velocity (Vxm) in the mediolateral direction (mean ± SD).**

Neck flexion/extension

Neck flexion/extension had a significant influence on most sway behaviour parameters except the mean COG projection. As shown in Table 10.5 there were significant increases in Sx ($p<0.01$), Sr, Sl as well as increases in Sy ($p<0.01$), Sa ($p<0.01$) and Sp ($p<0.01$) with neck extension compared with neutral. In addition, a significant increase in Sy with neck extension compared with flexion was observed, being due to the increase in Sp. There were significant increases in TL and TLx ($p<0.01$), as well as Vm and Vxm ($p<0.01$) with neck extension compared with neutral and flexion. There was also a significant ($p<0.01$) increase in Ay with neck extension compared with neutral and flexion.

Postural sway parameter	Neck flexion/extension		
	Extension	Neutral	Flexion
X (mm)	3.16 ± 2.23	3.16 ± 2.34	3.17 ± 2.31
Y (mm)	0.94 ± 2.27	0.91 ± 2.36	0.88 ± 2.40
Sx (mm)	1.22 ± 0.70 **	1.15 ± 0.63	1.19 ± 0.59
Sr (mm)	0.61 ± 0.38 *	0.58 ± 0.34	0.60 ± 0.33
Sl (mm)	0.61 ± 0.34 *	0.57 ± 0.33	0.59 ± 0.29
Sy (mm)	0.96 ± 0.49 ** +	0.89 ± 0.45	0.92 ± 0.43
Sa (mm)	0.47 ± 0.26 **	0.44 ± 0.23	0.46 ± 0.25
Sp (mm)	0.49 ± 0.26 ** +	0.45 ± 0.23	0.45 ± 0.20
TL (mm)	166.6 ± 130.7 * +	161.7 ± 133.7	159.5 ± 121.0
TLx (mm)	98.2 ± 79.0 ** ++	93.8 ± 82.1	92.5 ± 68.5
TLy (mm)	102.3 ± 84.4	100.4 ± 89.5	98.8 ± 82.4
Vm (mm/s)	8.35 ± 6.56 * +	8.11 ± 6.71	8.00 ± 6.07
Vxm (mm/s)	4.92 ± 3.96 ** ++	4.72 ± 4.10	4.64 ± 3.44
Vym (mm/s)	5.13 ± 4.24	5.03 ± 4.50	4.95 ± 4.14
Ay (°)	7.51 ± 46.8 ** +	2.91 ± 48.5	4.53 ± 46.7

* $p<0.05$, ** $p<0.01$ significantly greater than neutral.
+ $p<0.05$, ++ $p<0.05$ significantly greater than flexion.

Table 10.5 The influence of neck flexion/extension on the centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions, magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), total path length (TL), mediolateral (TLx) and anteroposterior (TLy) path lengths, mean velocity of sway (Vm), mediolateral (Vxm) and anteroposterior (Vym) sway velocities, and angle of sway from the sagittal plane (Ay) (mean ± SD).

Interaction between sex and vision

The analyses of variance showed a significant interaction between sex and vision for TLy and Vym. Standing with eyes open showed no significant difference in TLy and Vym between females and males, however, without visual feedback males exhibited a significant ($p<0.01$) increase in TLy and Vym compared with females (Table 10.6).

Postural sway parameter	Eyes open		Eyes closed	
	Females	Males	Females	Males
TLy (mm)	87.2 ± 74.8	95.9 ± 90.5	97.8 ± 66.4	126.2 ± 108.1 **
Vym (mm/s)	4.37 ± 3.76	4.80 ± 4.55	4.91 ± 3.33	6.33 ± 5.43 **

** significantly ($p<0.01$) greater than female value.

Table 10.6 The interaction between sex and vision on the total path length (TLy) and mean velocity (Vym) in the anteroposterior direction (mean ± SD).

Interaction between sex and neck rotation

The analyses of variance showed a significant interaction between sex and neck rotation for Sp only. As shown in Table 10.7 with rotation to the right compared with looking directly ahead there was significant increase Sp in females ($p<0.01$), but a significant decrease in males.

Postural sway parameter	Neck rotation		
	Left	Looking ahead	Right
Females Sp (mm)	0.45 ± 0.19	0.44 ± 0.19	0.47 ± 0.24 **
Males Sp (mm)	0.48 ± 0.24	0.49 ± 0.27	0.46 ± 0.26 *

* $p<0.05$, ** $p<0.01$ significantly greater or less than looking directly ahead.

Table 10.7 The interaction between sex and neck rotation on the magnitude of posterior sway (Sp) (mean ± SD).

Interaction between vision and sound

The analyses of variance showed significant interactions between vision and sound for X, Vm, Vxm and Vym. Although the initial analysis of variance showed a significant vision-sound interaction, the differerences were between inappropriate comparisons, i.e. eyes open with no sound compared with eyes closed at frequency 1595Hz.

Interaction between sex, vision and sound

The analyses of variance showed significant interactions between sex, vision and sound for TLy, Vm and Vym. As shown in Table 10.8 in both females and males either with eyes open or closed there were significant ($p<0.01$) decreases in TLy, Vm and Vym with no sound compared with sound. In addition, in males without visual feedback there were significant ($p<0.01$) reductions in TLy, Vm and Vym at 1595Hz compared with 2916Hz. However, with visual feedback TLy, Vm and Vym significantly ($p<0.01$) increased in males at frequency 1595Hz compared with 2916Hz. No significant difference was observed in females between the two frequencies, either with or without visual feedback.

Interaction between vision and neck rotation

The analyses of variance showed a significant interaction between vision and neck rotation for Y only. When standing with eyes open there was a significant ($p<0.01$) posterior shift of the COG projection with rotation to the left compared with looking directly ahead or rotation to the right (Table 10.9). With eyes closed there were no significant differences between any neck position.

Eyes open

Postural sway parameter	Frequency		
	No sound	1595 Hz	2916 Hz
Females			
TLy (mm)	56.7 ± 8.65 **	102.7 ± 93.3	102.2 ± 82.0
Vm (mm/s)	4.49 ± 0.67 **	8.49 ± 7.35	8.52 ± 5.98
Vym (mm/s)	2.84 ± 0.43 **	5.15 ± 4.68	5.13 ± 4.11
Males			
TLy (mm)	49.4 ± 5.63 **	119.6 ± 126.6 ++	118.8 ± 73.7
Vm (mm/s)	3.93 ± 0.42 **	9.80 ± 10.3 ++	9.51 ± 5.25
Vym (mm/s)	2.45 ± 0.38 **	6.00 ± 6.6 ++	5.96 ± 3.70

** significantly ($p<0.01$) less than frequencies 1595Hz and 2916Hz.
++ significantly ($p<0.01$) greater than frequency 2916Hz.

Eyes closed

Postural sway parameter	Frequency		
	No sound	1595 Hz	2916 Hz
Females			
TLy (mm)	63.1 ± 13.0 **	119.8 ± 87.3	110.7 ± 60.4
Vm (mm/s)	5.05 ± 0.99 **	9.90 ± 5.78	9.27 ± 4.11
Vym (mm/s)	3.15 ± 0.65 **	6.01 ± 4.38	5.55 ± 3.03
Males			
TLy (mm)	57.6 ± 10.7 **	141.7 ± 88.6 ++	179.3 ± 139.7
Vm (mm/s)	4.64 ± 0.84 **	11.3 ± 6.59 ++	14.0 ± 10.31
Vym (mm/s)	2.88 ± 054 **	7.11 ± 4.45 ++	9.00 ± 7.01

** significantly ($p<0.01$) less than frequencies 1595Hz and 2916Hz.
++ significantly ($p<0.01$) less than frequency 2916Hz.

Table 10.8 The interaction between sex, vision and sound on the total path length in the anteroposterior direction (TLy), mean sway velocity (Vm) and mean velocity of sway in the anteroposterior direction (Vym) (mean ± SD).

Postural sway parameter	Neck rotation		
	Left	Looking ahead	Right
Eyes open			
Y (mm)	0.85 ± 2.33 **	1.01 ± 2.41	1.01 ± 2.34
Eyes closed			
Y (mm)	0.88 ± 2.31	0.88 ± 2.38	0.84 ± 2.31

** significantly ($p<0.01$) less than looking directly ahead and rotation to the right.

Table 10.9 The interaction between vision and neck rotation on the anteroposterior centre of gravity projection (Y) (mean ± SD).

Interaction between vision and neck flexion/extension

A significant interaction between vision and neck flexion/extension was observed for Sl, Sy, Sa, Sp and Ay. As shown in Table 10.10 there were significant increases in Sl, Sy ($p<0.01$) and Sa ($p<0.01$) with eyes open and neck flexion compared with neutral. There was no difference between neck flexion/extension for Sp and Ay. In contrast, without visual feedback there was no significant difference in Sl, but a significant ($p<0.01$) decrease in Sy, Sp and Ay with the neck in neutral or flexed compared with extension. There was also a significant ($p<0.01$) decrease in Sa with the neck in neutral compared with extension.

Postural sway parameter	Neck flexion/extension		
	Extension	Neutral	Flexion
Eyes open			
Sl (mm)	0.49 ± 0.28	0.47 ± 0.23	0.52 ± 0.26 *
Sy (mm)	0.77 ± 0.39	0.75 ± 0.37	0.80 ± 0.35 **
Sa (mm)	0.38 ± 0.19	0.36 ± 0.18	0.40 ± 0.19 **
Sp (mm)	0.39 ± 0.22	0.38 ± 0.22	0.40 ± 0.17
Ay (^{0})	5.11 ± 51.3	3.36 ± 52.2	4.44 ± 49.2
Eyes closed			
Sl (mm)	0.72 ± 0.36	0.67 ± 0.38	0.67 ± 0.31
Sy (mm)	1.14 ± 0.52	1.04 ± 0.46 ++	1.03 ± 0.47 ++
Sa (mm)	0.57 ± 0.29	0.52 ± 0.25 ++	0.53 ± 0.29
Sp (mm)	0.58 ± 0.26	0.52 ± 0.23 ++	0.51 ± 0.21 ++
Ay (^{0})	9.92 ± 41.8	2.46 ± 44.7 ++	4.62 ± 44.2 ++

* $p<0.05$, ** $p<0.01$ significantly greater than neutral.
++ significantly ($p<0.01$) less than extension.

Table 10.10 The interaction between vision and neck flexion/extension on the magnitude of sway to the left (Sl), mean sway magnitude in the anteroposterior direction (Sy) (separately anteriorly (Sa) and posteriorly (Sp)) and angle of sway from the sagittal plane (Ay) (mean ± SD).

Interaction between sound and neck rotation

A significant interaction was observed between sound and neck rotation for Y, TLx and Vxm. With no sound there was a significant ($p<0.01$) posterior shift of the COG projection with rotation either to the right or left compared with looking directly ahead (Table 10.11). At 1595Hz there was a significant posterior shift of the COG projection with rotation to the left compared with rotation to the right. There was no difference in the anteroposterior COG projection between any neck position at 2916Hz.

For TLx and Vxm there was no difference for any neck position without sound. In contrast, at 1595Hz there was a significant ($p<0.01$) decrease in TLx and Vxm with rotation to the left and looking directly ahead compared with rotation to the right. At 2916Hz both TLx and Vxm were significantly reduced with the neck rotated to the left compared with rotation to the right (Table 10.11).

Postural sway parameter	**Frequency**	**Neck rotation**		
		Left	**Looking ahead**	**Right**
Y (mm)	**No sound**	2.11 ± 2.60 **	2.28 ± 2.52	2.10 ± 2.54 **
	1595 Hz	0.19 ± 1.81 +	0.27 ± 1.97	0.38 ± 2.05
	2916 Hz	0.27 ± 1.94	0.28 ± 2.08	0.29 ± 1.90
TLx (mm)	**No sound**	56.9 ± 11.8	56.3 ± 11.2	56.6 ± 12.2
	1595 Hz	101.4 ± 49.7 ++	101.2 ± 58.7 ++	134.3 ± 141.3
	2916 Hz	107.9 ± 55.3 +	114.6 ± 84.9	124.1 ± 96.4
Vxm (mm)	**No sound**	2.84 ± 0.59	2.82 ± 0.56	2.83 ± 0.61
	1595 Hz	5.09 ± 2.50 ++	5.08 ± 2.94 ++	6.74 ± 7.09
	2916 Hz	5.47 ± 2.65 +	5.75 ± 4.26	6.23 ± 4.84

** significantly ($p<0.01$) less than looking directly ahead.
+ $p<0.05$, ++ $p<0.01$ significantly less than rotation to the right.

Table 10.11 The interaction between sound and neck rotation on the anteroposterior centre of gravity projection (Y), total path length and mean velocity of sway in the mediolateral direction (TLx and Vxm) (mean ± SD).

Interaction between sex, sound and neck rotation

The analyses of variance revealed a significant interaction between sex, sound and neck rotation for Y. Table 10.12 shows that in females without sound there was a significant ($p<0.01$) posterior shift of the COG projection with rotation either to the right or left compared with looking directly ahead. At 1595Hz the COG projection exhibited a significant backward shift with rotation to the left, while a significant ($p<0.01$) forward shift with rotation to the right was observed compared with looking directly ahead. In addition, there was a significant ($p<0.01$) shift of the COG projection with neck rotation to the left compared with rotation to the right. In males (Table 10.12) without sound there was a significant posterior shift of the COG projection with rotation to the left compared with looking ahead, but no difference with any neck position at 1595Hz and 2916Hz.

Postural sway parameter	Frequency	Neck rotation		
		Left	Looking ahead	Right
Females	No sound	2.86 ± 3.24 **	3.02 ± 3.12	2.80 ± 3.16 **
Y (mm)	1595 Hz	0.11 ± 1.61 * ++	0.29 ± 1.92	0.47 ± 1.94 **
	2916 Hz	0.36 ± 1.83	0.32 ± 1.86	0.41 ± 1.83
Males	No sound	1.12 ± 0.41 *	1.28 ± 0.49	1.16 ± 0.45
Y (mm)	1595 Hz	0.31 ± 2.06	0.25 ± 2.06	0.27 ± 2.20
	2916 Hz	0.16 ± 2.10	0.23 ± 2.37	0.12 ± 1.99

* $p<0.05$, ** $p<0.01$ significantly greater or less than looking directly ahead.
++ significantly ($p<0.01$) less than rotation to the right.

Table 10.12 The interaction between sex, sound and neck rotation on the anteroposterior centre of gravity projection (Y) (mean ± SD).

Interaction between sound and neck flexion/extension

Table 10.13 shows that there is a significant interaction between sound and neck flexion/extension for Y.

Postural sway parameter	Frequency	Neck flexion/extension		
		Extension	Neutral	Flexion
Y (mm)	No sound	2.10 ± 2.53 **	2.25 ± 2.54	2.13 ± 2.60 **
	1595 Hz	0.38 ± 1.86 * +	0.24 ± 1.95	0.23 ± 2.03
	2916 Hz	0.33 ± 1.91 *	0.24 ± 1.98	0.27 ± 2.04

* $p<0.05$, ** $p<0.01$ significantly greater or less than neutral.
\+ significantly ($p<0.05$) greater than flexion.

Table 10.13 The interaction between sound and neck flexion/extension on the anteroposterior centre of gravity projection (Y) (mean ± SD).

Without sound a significant ($p<0.01$) posterior shift of the COG projection was observed with neck extension and flexion compared with neutral. However, at 1595Hz and 2916Hz there was a significant anterior shift of the COG projection with neck extension compared with neutral. In addition, there was significant forward movement of the COG projection with neck extension compared with flexion at 1595Hz.

Interaction between neck rotation and neck flexion/extension

The analyses of variance showed a significant interaction between neck rotation and neck flexion/extension for Sr only. As shown in Table 10.14 with rotation to the right the magnitude of sway towards the right was significantly greater with neck extension ($p<0.01$) and flexion than with neutral. Furthermore, a significant increase in Sr was observed with neck extension compared with flexion. No differences were observed with rotation to the left or when looking directly ahead.

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
Sr (mm)	Left	0.60 ± 0.31	0.57 ± 0.27	0.60 ± 0.29
	Looking ahead	0.57 ± 0.33	0.59 ± 0.39	0.58 ± 0.31
	Right	0.67 ± 0.47 ** +	0.57 ± 0.36	0.62 ± 0.37 *

* $p<0.05$, ** $p<0.01$ significantly greater than neutral.
+ significantly ($p<0.05$) greater than flexion.

Table 10.14 The interaction between neck rotation and neck flexion/extension on the magnitude of sway to the right (Sr) (mean ± SD).

Interaction between sex, neck rotation and neck flexion/extension

A significant interaction between sex, neck rotation and neck flexion/extension was observed for Ay (Table 10.15). In females when looking directly ahead the angle of sway from the sagittal plane was significantly greater with neck extension and flexion than in neutral. In contrast, in males when looking directly ahead the angle of sway from the sagittal plane was significantly less with neck extension and flexion than in neutral. Furthermore, there was a significant ($p<0.01$) decrease in Ay with neck extension compared with flexion. No differences with rotation to the right or left were observed.

Postural sway parameter	Neck Rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
Females	**Left**	14.3 ± 44.4	12.5 ± 44.6	9.88 ± 43.6
Ay (^{0})	**Looking ahead**	12.5 ± 45.3 *	4.38 ± 47.3	12.2 ± 44.4 *
	Right	22.0 ± 47.5	14.9 ± 47.8	12.6 ± 46.9
Males	**Left**	-4.79 ± 44.8	-5.67 ± 46.0	-3.16 ± 47.8
Ay (^{0})	**Looking ahead**	-0.16 ± 46.2 * ++	-9.81 ± 48.4	-8.50 ± 47.9 *
	Right	-7.41 ± 46.9	-6.54 ± 54.1	-2.85 ± 47.9

* significantly (p<0.05) greater or less than neutral.
++ significantly (p<0.01) greater than flexion.

Table 10.15 The interaction between sex, neck rotation and neck flexion/extension on the angle of sway from the sagittal plane (Ay) (mean ± SD).

Interaction between vision, sound and neck rotation

As shown in Table 10.16 with visual feedback and no sound there was a significant (p<0.01) posterior shift of the COG projection with the neck rotated either to the right or left compared with looking directly ahead. In addition, with eyes open and at 1595Hz there was also a significant (p<0.01) posterior shift of the COG projection with the neck rotated to left compared with looking directly ahead or rotation to the right. No differences for neck rotation with eyes open at 2916Hz were observed. Without visual feedback, either with or without sound no differences were observed.

Interaction between vision, sound and neck flexion/extension

A significant interaction between vision, sound and neck flexion/extension was observed for SI only (Table 10.17). Both with and without visual feedback, either without sound or at 1595Hz there were no significant differences for any neck flexion/extension position. However, at 2916Hz with eyes open there was a significant (p<0.01) decrease in SI with the neck in neutral compared with flexion. In addition, at 2916 Hz without visual feedback there was a significant (p<0.01) decrease in SI with neck flexion compared with extension.

Postural sway parameter	Frequency	Neck rotation		
		Left	Looking ahead	Right
Eyes open	**No sound**	2.15 ± 2.62 **	2.40 ± 2.58	2.11 ± 2.57 **
Y (mm)	**1595 Hz**	0.13 ± 1.75 ++	0.33 ± 1.93	0.55 ± 2.22
	2916 Hz	0.26 ± 1.98	0.29 ± 2.07	0.38 ± 1.81
Eyes closed	**No sound**	2.08 ± 2.61	2.15 ± 2.49	2.08 ± 2.52
Y (mm)	**1595 Hz**	0.26 ± 1.88	0.22 ± 2.02	0.22 ± 1.87
	2916 Hz	0.28 ± 1.92	0.27 ± 2.12	0.20 ± 1.99

** significantly ($p<0.01$) less than looking directly ahead.
++ significantly ($p<0.01$) less than looking directly ahead and rotation to the right.

Table 10.16 The interaction between vision, sound and neck rotation on the anteroposterior centre of gravity projection (Y) (mean ± SD).

Postural sway parameter	Frequency	Neck flexion/extension		
		Extension	Neutral	Flexion
Eyes open	**No sound**	0.34 ± 0.14	0.33 ± 0.10	0.34 ± 0.11
Sl (mm)	**1595 Hz**	0.56 ± 0.29	0.52 ± 0.21	0.55 ± 0.22
	2916 Hz	0.58 ± 0.29	0.57 ± 0.27 **	0.66 ± 0.30
Eyes closed	**No sound**	0.52 ± 0.19	0.48 ± 0.15	0.52 ± 0.21
Sl (mm)	**1595 Hz**	0.79 ± 0.37	0.72 ± 0.30	0.73 ± 0.29
	2916 Hz	0.85 ± 0.38 **	0.81 ± 0.52	0.75 ± 0.34

** significantly ($p<0.01$) greater or less than flexion.

Table 10.17 The interaction between vision, sound and neck flexion/extension on the magnitude of sway to the left (Sl) (mean ± SD).

Interaction between sound, neck rotation and neck flexion/extension

As shown in Table 10.18 without sound when looking directly ahead there was a significant ($p<0.01$) posterior shift of the anteroposterior COG projection with neck extension and flexion compared with neutral. At 1595Hz with rotation to the left there was a significant ($p<0.01$) posterior movement of the COG projection with flexion compared with extension. Looking directly ahead there was a significant ($p<0.01$) posterior shift of the COG projection with neck flexion or neutral compared with extension. At 2916Hz no differences in Y were observed for any combinations of neck rotation and flexion/extension.

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
No sound				
	Left	2.07 ± 2.62	2.14 ± 2.61	2.13 ± 2.65
Y (mm)	**Looking ahead**	2.14 ± 2.51 **	2.53 ± 2.49	2.16 ± 2.61 **
	Right	2.10 ± 2.52	2.08 ± 2.55	2.11 ± 2.61
Frequency 1595 Hz				
	Left	0.31 ± 1.91	0.19 ± 1.80	0.08 ± 1.76 ++
Y (mm)	**Looking ahead**	0.44 ± 2.00	0.19 ± 1.96 ++	0.20 ± 1.99 ++
	Right	0.40 ± 1.70	0.34 ± 2.11	0.41 ± 2.34
Fequency 2916 Hz				
	Left	0.31 ± 1.93	0.28 ± 1.95	0.23 ± 1.98
Y (mm)	**Looking ahead**	0.34 ± 2.02	0.23 ± 2.12	0.27 ± 2.16
	Right	0.34 ± 1.82	0.20 ± 1.90	0.32 ± 2.01

** significantly ($p<0.01$) less than neutral.
++ significantly ($p<0.01$) less than extension.

Table 10.18 The interaction between sound, neck rotation and neck flexion/extension on the anteroposterior centre of gravity projection (Y) (mean ± SD).

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
No sound				
	Left	30.8 ± 34.4	34.2 ± 32.2	33.1 ± 35.8
Ay (^{0})	**Looking ahead**	32.2 ± 34.9	28.5 ± 33.3	33.7 ± 32.9
	Right	36.9 ± 31.2	33.6 ± 36.8	34.0 ± 34.0
Frequency 1595 Hz				
	Left	-7.72 ± 49.0	-15.8 ± 49.1 **	-12.1 ± 47.2
Ay (^{0})	**Looking ahead**	-3.46 ± 51.3	-19.9 ± 49.7 **	-15.0 ± 47.6 **
	Right	-5.67 ± 54.1	-4.40 ± 58.2	-7.64 ± 54.8
Frequency 2916 Hz				
	Left	-4.77 ± 42.0	-4.35 ± 39.6	-8.10 ± 39.9
Ay (^{0})	**Looking ahead**	-7.62 ± 40.1	-13.7 ± 45.3	-8.74 ± 43.6
	Right	-3.09 ± 48.2	-11.9 ± 46.2	-8.39 ± 40.0

** significantly ($p<0.01$) greater than extension.

Table 10.19 The interaction between sound, neck rotation and neck flexion/extension on the angle of sway from the sagittal plane (Ay) (mean ± SD).

For Ay (Table 10.19) both with no sound and at 2916Hz there were no differences with any combination of neck rotation and flexion/extension. In contrast, at 1595Hz with rotation to the left there was a significant ($p<0.01$)

increase in Ay with the neck in neutral compared with extension. Furthermore, when looking directly ahead there was a significant ($p<0.01$) increase in Ay with the neck in neutral or flexion compared with extension.

Interaction between sex, vision, sound, neck rotation and neck flexion/extension

A significant interaction between sex, vision, sound, neck rotation and neck flexion/extension for Y was observed (Table 10.20 and 10.21). In females (Table 10.20) with eyes open and without sound and when looking directly ahead the anteroposterior COG projection was significantly ($p<0.01$) shifted posteriorly with neck extension and flexion compared with looking directly ahead. Furthermore, at 1595Hz when looking directly ahead there was a significant anterior shift of the COG projection with neck extension compared with neutral. When rotated to the right there was also a significant anterior shift of the COG projection with neck extension compared with flexion.

As can be also seen in Table 10.20 with the eyes closed and without sound there was a significant posterior shift in the COG projection in females with the neck flexed compared with neutral or when looking directly ahead ($p<0.01$) or with rotation to the right. Furthermore, at 1595Hz there was significant posterior shift of the COG projection with neck flexion compared with neutral, while at 2916Hz there was a significant anterior shift of the COG projection with neck extension compared with flexion.

As shown in Table 10.21 for males with eyes open and without sound when looking directly ahead there was a significant posterior shift of the COG projection with neck extension ($p<0.01$) and flexion compared with looking directly ahead. At both 1595Hz and 2916Hz there were no differences for any neck flexion/extension positions when looking either directly ahead or rotation to the right or left. Without visual feedback no differences were observed.

Females, Eyes open

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
No sound				
	Left	2.94 ± 3.28	2.94 ± 3.39	2.88 ± 3.40
Y (mm)	**Looking ahead**	2.98 ± 3.31 **	3.55 ± 3.09	3.03 ± 3.37 **
	Right	2.79 ± 3.24	2.81 ± 3.26	2.86 ± 3.41
Frequency 1595 Hz				
	Left	0.20 ± 1.83	0.10 ± 1.67	0.05 ± 1.61
Y (mm)	**Looking ahead**	0.51 ± 2.11 *	0.27 ± 1.90	0.33 ± 2.25
	Right	0.91 ± 2.02 +	0.63 ± 2.09	0.56 ± 2.15
Frequency 2916 Hz				
	Left	0.43 ± 1.87	0.44 ± 1.92	0.31 ± 1.95
Y (mm)	**Looking ahead**	0.39 ± 1.88	0.27 ± 1.84	0.40 ± 1.84
	Right	0.59 ± 1.65	0.46 ± 1.82	0.53 ± 1.88

* $p<0.05$, ** $p<0.01$ significantly greater or less than neutral.
+ significantly ($p<0.05$) greater than flexion.

Females, Eyes closed

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
No sound				
	Left	2.88 ± 3.38	2.86 ± 3.28	2.66 ± 3.43
Y (mm)	**Looking ahead**	2.79 ± 3.26	3.01 ± 3.21	2.77 ± 3.09 **
	Right	2.79 ± 3.22	2.86 ± 3.20	2.69 ± 3.33 *
Frequency 1595 Hz				
	Left	0.22 ± 1.75	0.15 ± 1.75	-0.09 ± 1.34
Y (mm)	**Looking ahead**	0.36 ± 1.78	0.17 ± 2.03	0.08 ± 1.77 *
	Right	0.34 ± 1.66	0.13 ± 1.67	0.24 ± 2.29
Frequency 2916 Hz				
	Left	0.37 ± 1.84	0.30 ± 1.85	0.30 ± 1.92
Y (mm)	**Looking ahead**	0.34 ± 1.90	0.26 ± 2.03	0.26 ± 2.03
	Right	0.42 ± 1.97 +	0.25 ± 1.98	0.22 ± 2.01

* $p<0.05$, ** $p<0.01$ significantly less than neutral.
+ significantly ($p<0.05$) greater than flexion.

Table 10.20 The interaction for females between vision, sound, neck rotation and neck flexion/extension on the anteroposterior centre of gravity projection (Y) (mean ± SD).

Males, Eyes open

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
No sound				
	Left	1.11 ± 0.42	1.10 ± 0.46	1.14 ± 0.41
Y (mm)	Looking ahead	1.17 ± 0.47 **	1.69 ± 0.40	1.24 ± 0.58 *
	Right	1.19 ± 0.49	1.09 ± 0.53	1.19 ± 0.47
Frequency 1595 Hz				
	Left	0.25 ± 1.95	0.22 ± 1.95	-0.05 ± 2.01
Y (mm)	Looking ahead	0.52 ± 2.09	0.13 ± 1.71	0.14 ± 1.82
	Right	0.02 ± 1.27	0.38 ± 2.89	0.61 ± 3.10
Frequency 2916 Hz				
	Left	0.06 ± 2.23	0.12 ± 2.26	0.07 ± 2.22
Y (mm)	Looking ahead	0.17 ± 2.06	0.26 ± 2.56	0.21 ± 2.84
	Right	0.12 ± 1.96	0.11 ± 2.00	0.29 ± 2.06

* $p<0.05$, ** $p<0.01$ significantly less than neutral.

Males, Eyes closed

Postural sway parameter	Neck rotation	Neck flexion/extension		
		Extension	Neutral	Flexion
No sound				
	Left	1.07 ± 0.39	1.17 ± 0.48	1.13 ± 0.41
Y (mm)	Looking ahead	1.15 ± 0.42	1.37 ± 0.38	1.09 ± 0.52
	Right	1.15 ± 0.41	1.06 ± 0.45	1.25 ± 0.43
Frequency 1595 Hz				
	Left	0.65 ± 2.42	0.34 ± 2.18	0.46 ± 2.34
Y (mm)	Looking ahead	0.35 ± 2.35	0.16 ± 2.47	0.22 ± 2.37
	Right	0.17 ± 1.79	0.21 ± 2.08	0.23 ± 2.20
Frequency 2916 Hz				
	Left	0.30 ± 2.14	0.18 ± 2.14	0.21 ± 2.21
Y (mm)	Looking ahead	0.47 ± 2.59	0.10 ± 2.49	0.18 ± 2.33
	Right	0.12 ± 1.97	-0.10 ± 2.09	0.20 ± 2.43

Table 10.21 The interaction for males between vision, sound, neck rotation and neck flexion/extension on the anteroposterior centre of gravity projection (Y) (mean ± SD).

10.4 Discussion

The subject's characteristic showed a similar and consistent difference as presented in the Experiments 1 (Chapter 4) and 3 (Chapter 7).

Gender appears to influence the mediolateral projection of the COG, with females showing a greater deviation than males. The interaction between sex and vision suggests that vision is more important in males than females: this finding agrees with that of Kollegger et al. (1992). Vision has been reported to be more important in the control of posture in the mediolateral direction (Kollegger et al, 1989; Day et al. 1993). Furthermore, vision in males appears to be more important in the anteroposterior direction as seen in the control of path length and the mean velocity of sway.

The visual, auditory, neck proprioceptor and vestibular systems all have an influence on postural sway behaviour, with vision appearing to be the stabilising factor in postural control as reported in several previous studies (Kollegger et al. 1989; 1992; Colledge et al. 1994). Generally, sound has been shown to cause postural instability (Juntunen et al. 1987; Raper and Soames, 1991; Kilburn et al. 1992 Soames and Raper 1992). However, sound changes the mean angle of sway with some sound frequencies leading to postural stability compared with others: this finding confirms those of Sakellari and Soames (1996). Although anteroposterior sway is clearly influenced by the sound frequency (Sakellari and Soames 1996), mediolateral sway also appears to be affected by the frequency of sound. Feedback from the neck proprioceptors decreases postural stability by increasing the total path length and the mean velocity of sway in the mediolateral direction. Neck extension, by changing the orientation of the vestibular system, leads to postural instability, including a significant change in the angle of sway. The effect of neck extension on the vestibular system has been suggested to be due to the repositioning of the vestibular system (Jackson and Epstein 1991).

The observation of an interaction between sex and neck rotation showed that neck proprioception induced a backward movement in females but helped to stabilise sway in this direction in males. This implies that there is a difference in neck proprioception regulating posterior sway between the sexes.

The interaction between sex, vision and sound also shows a sex difference. The interaction between vision and auditory inputs has a negative effect on postural sway in males by increasing the anteroposterior path length and sway velocity. In addition, the increase in anteroposterior sway velocity leads to an increase in the mean velocity of sway. The visual-auditory interaction has been found to destabilise posture (Sakellari and Soames 1996). It is further suggested that such interaction causes postural instability in males.

The posterior shift of the COG projection observed with vision and neck rotation may be due to a mismatch between visual feedback and neck proprioception, since without visual feedback there is no backward shift of the COG projection accompanying neck rotation. The interaction leads to a greater backward shift with rotation to the left than to the right. The reason for this is unclear, however the current experiment shows that there is a tendency for the COG projection to be displaced when neck rotation is to the left.

The interaction between vision and neck flexion/extension indicates that the visual system assists vestibular input associated with neck extension in controlling the magnitude of sway in the anteroposterior direction, as well as the angle of sway from the sagittal plane. In contrast, the visual system combining with the vestibular input associated with neck flexion increases sway magnitude to the left and anteriorly. The interaction between visual and vestibular inputs associated with neck flexion appears to destabilise posture by increasing body sway to the left and anteriorly since without visual feedback neck flexion stabilises posture.

The COG projection in the anteroposterior direction, the total path length and the mean velocity of sway in the mediolateral direction were all influenced by the interaction between sound and neck rotation. The anterior shift of the COG projection and the increase in the total path length and mean velocity of sway in the mediolateral direction when the neck was rotated to the right may be related to handedness. It is also possible that one ear is more dominant than the other leading to leaning towards the preferred side. The interaction between the auditory and neck proprioceptors seems to depends on the auditory input. For the anteroposterior COG projection without sound it is the neck input which cause the instability. However, with sound the interaction with neck proprioception leads to no change in the position of the COG projection. For the total path length and the mean velocity of sway in the mediolateral direction without sound neck rotation has no effect but with sound there is an increase in the mediolateral path length and velocity of sway with rotation to the right compared with looking directly ahead. From these findings it is suggested that the interaction between auditory and neck proprioceptor input stabilises sway in the anteroposterior direction, but destabilises it in the mediolateral direction. The destabilising effect of such an interaction is possible since sound is known to increase sway in the mediolateral direction (Sakellari and Soames 1996), while neck proprioceptor input causes the body to sway to the side of stimulation (Smetanin et al. 1993). It is possible that auditory and neck proprioceptive inputs are additive and lead to postural instability in the mediolateral direction.

The interaction between sex, sound and neck rotation also influenced the COG projection in the anteroposterior direction, with the interaction between sound and neck rotation showing a sex difference. The interaction appears to have a greater influence females, with auditory input decreasing the destabilising effect of neck proprioception.

Although it has been suggested that there is no vestibular-auditory interaction in man (Soames and Raper 1992), the interaction between sound and neck flexion/extension was observed to influence the COG projection in the anteroposterior direction. It is suggested that sound compounds the postural instability induced by neck extension. Combined with vestibular input the effect of sound is similar to the effect of vision on postural control. Sound acts as a stabilising cue and reduces the postural destabilisation induced by the vestibular system.

The finding that neck rotation and neck flexion/extension increases the magnitude of sway to the right confirms the linear integration of the vestibular and neck proprioceptor systems (Anatasopoulos and Mergner 1982; Karnath et al. 1994), since neck proprioceptor input induces sway to the side of stimulation (Smetanin et al. 1993) and vestibular stimulation increases postural sway (Karnath et al. 1994). In addition, neck extension has a more powerful effect than flexion on postural control. It has been observed that the interaction between neck proprioceptor and vestibular input with neck extension produces a greater magnitude of sway to the right than it does with neck flexion.

The interaction between sex, neck rotation and neck flexion/extension influences the angle of sway from the sagittal plane. Such interaction shows difference in vestibular input between females and males and that it is the vestibular input which causes postural destabilisation in females by increasing the angle of sway. In contrast, the vestibular input leads to postural stability in males by decreasing the angle of sway. In addition, in males there is also a difference in vestibular input between neck extension and flexion in controlling the angle of sway.

The interaction between vision, sound and neck rotation influences the anteroposterior COG projection. From the findings visual feedback appears to be the destabilising factor in the interaction with neck proprioceptor input, however the mismatch is reduced by sound. The auditory system is, therefore the stabilising factor in the interaction between the visual, auditory and neck proprioceptor systems. The posterior shift of the COG projection at 1595Hz with neck rotation to the left with visual feedback may be due to the handedness.

The interaction between vision, sound and neck flexion/extension influences sway magnitude to the left. The interaction indicates that the destabilising effect of sound affects the vestibular system leading to postural destabilisation in the mediolateral direction.

The interaction between sound, neck rotation and neck flexion/extension tends to stabilise posture by shifting the COG projection forward and decreasing the angle of sway, particularly at the stabilising frequency of sound. Sound appears to decrease the mismatch between neck rotation and neck extension, since without sound there is a tendency to move the COG projection backward and to increase the angle of sway from the sagittal plane. With the destabilising effect of sound, even though there is no significant difference, there is a tendency for a forward shift of the COG projection and a decrease in the angle of sway from the sagittal plane. Thus, it is suggested that the interaction between the auditory, neck proprioceptor and vestibular systems increases postural stability with the auditory input being an important cue in promoting stabilisation.

The interaction between vision, sound, neck rotation and neck flexion/extension shows a forward movement of the COG projection in females, with sound appearing to be the crucial cue since there is tendency to shift the COG projection forward at both sound frequencies. It is suggested that the interaction between the visual, auditory, neck proprioceptor and vestibular systems increases postural stability in females, with the auditory system being the important factor in compromising the mismatch between vision, vestibular and neck proprioception.

10.5 Summary

The responses to visual, auditory and static vestibular and neck proprioception all influence postural maintenance. Visual feedback leads to postural stabilisation, whereas auditory and neck proprioceptor stimulation causes postural destabilisation. The vestibular system depends on the nature of the input, with neck extension causing postural instability. The visual-vestibular, visual-neck proprioceptor and vestibular-neck proprioceptor interactions all result in postural destabilisation. The interaction between auditory-vestibular inputs increases stability in the anteroposterior direction, whereas the combination of auditory and neck proprioceptor inputs leads to postural instability in the mediolateral direction. These interactions depend on the auditory system being the stabilising cue. The visual-auditory-neck proprioceptor combination appears to stabilise the anteroposterior direction with the auditory input reducing the mismatch between vision and neck proprioceptor cues. The visual-auditory-vestibular interaction leads to postural instability in the mediolateral direction with the auditory system acting as the destabilising factor. The auditory-vestibular-neck proprioception interaction stabilises posture in the anteroposterior direction and decreases the deviation of the body from the sagittal plane, with the auditory input being the stabilising cue. It appears, therefore that auditory cues have an important role in postural maintenance, with the precise effect (stabilising or destabilising) depending on the nature of other sensory inputs.

Chapter 11

Responses to auditory and dynamic vestibular and neck proprioceptor stimulation while tracking a moving target

11.1 Introduction

The individual influence of vestibular (Keshner et al. 1987; Horak et al. 1990), neck proprioceptor (Lund 1980; Smetanin et al. 1993; Koskimies et al. 1997) and the auditory system (Juntunen et al. 1987; Raper and Soames 1991; Kilburn et al. 1992; Soames and Raper 1992; Sakellari and Soames 1996) on postural control is well established. The fact that sound can destabilise posture suggests that there may be damage to the eighth cranial nerve (Juntunen et al. 1987; Kilburn et al. 1992). The vestibular-auditory and neck proprioceptor-auditory interactions have yet to be investigated in man and their importance for postural regulation established. The aim of the present chapter is to investigate individual and combinations of the effects of dynamic vestibular, neck proprioceptor and auditory inputs on the postural sway behaviour.

11.2 Materials and methods

Twenty-two healthy subjects (12 females, 10 males), aged between 18 and 30 years, agreed to participate in this experiment.

Eight combinations of head-neck posture were employed while tracking a moving target, each at two velocities of head movement (0.2m/s and 1.0m/s) and with three conditions of sound (no sound, 1595Hz and 2916Hz). For tracking targets moving horizontally the neck was either in neutral (N), extended (E) or flexed (F) 45^0, while when tracking vertically the subject was either looking directly ahead (A) or the neck was rotated to the right (R) or left (L) 45^0. In the remaining two conditions the subject tracked obliquely from neck extended and rotated to the right to flexed and rotated to the left (RE) or from neck extended and rotated to the left to flexed and rotated to the right (LE).

Four-way analyses of variance were conducted for each sway parameter (Chapter 3 part 3.3) with sex, sound, velocity of head movement and direction of head movement as independent variables in order to determine the influence of each variable on postural sway behaviour. t-tests were further conducted to determined the difference within each independent variable influencing each postural sway parameter. In addition, t-tests were conducted on the subject characteristics. The 5% level of significance was used unless otherwise stated.

11.3 Results

11.3.1 Subject characteristics

The characteristics of the population studied are given in Table 11.1, with the data being presented for the whole group as well as for females and males separately. There was no difference in age between females and males, however, height, foot length and eye level height were all significantly ($p<0.01$) greater and eye-object distance was significantly ($p<0.01$) smaller in males.

Subject characteristics	All	Females	Males
Age (year)	24.0 ± 4.16	24.5 ± 3.94	23.3 ± 4.52
Height (cm)	166.5 ± 10.0	160.6 ± 9.38	173.7 ± 4.69 **
Foot length (cm)	24.2 ± 1.43	23.3 ± 0.86	25.3 ± 1.27 **
Eye-Object distance (cm)	49.3 ± 1.43	50.2± 0.86	48.3 ± 1.27 **
Eye level height (cm)	156.0 ± 9.83	150.4 ± 9.76	162.6 ± 4.38 **

** significantly ($p<0.01$) greater or less than female value.

Table 11.1 The characteristics of the subjects (12 females, 10 males) who participated in Experiments 2 and 4 (mean + SD).

11.3.2 Analyses of variance

The results of the various analyses of variance are presented in Appendix 12, showing the influence of sex, sound, the velocity and direction of head movement, as well as their interactions on the various parameters of postural sway behaviour.

Sex

Few difference in sway behaviour were observed between the female and male groups, the difference being restricted to X. There was a significant ($p<0.01$) shift of the COG projection to the right in females (4.04 ± 2.14) compared to males (2.36 ± 1.81).

Sound

As shown in Table 11.2 sound had no influence on the COG projection in either the mediolateral or anteroposterior directions. At 1595Hz and 2916Hz compared to the no sound condition there was a significant ($p<0.01$) increase in the magnitude of sway in both the mediolateral and anteroposterior directions, but a significant ($p<0.01$) decrease in total path length and mean velocity of sway in both the mediolateral and anteroposterior directions. The effect of sound also caused a significant ($p<0.01$) deviation of the body with respect to the angle of sway. At 1595Hz compared with 2916Hz there was a significant increase in mediolateral sway magnitude due to significant increase in Sl, an increase in Sa, an increase TL due to the significant increase TLx, and an increase Vm due to the significant increase in Vxm.

Velocity of head movement

The velocity of head movement influenced all sway behaviour parameters, except the COG projection in both the mediolateral and anteroposterior directions. Table 11.3 shows that the higher velocity resulted in a significant ($p<0.01$) increase in Sx as well as separately to the right and left, and Sy including anteriorly and posteriorly separately. Similarly, the higher velocity also significantly ($p<0.01$) increased total path length and its mediolateral and anteroposterior components. A similar pattern was observed for the mean velocity of sway and the mean mediolateral and anteroposterior velocities separately. There was a significant ($p<0.01$) reduction in the angle of sway from the sagittal plane at the higher velocity of head movement.

Postural sway parameter	**Frequency**		
	No sound	**1595 Hz**	**2916 Hz**
X (mm)	3.03 ± 2.23	3.42 ± 2.16	3.39 ± 2.08
Y (mm)	0.42 ± 2.25	0.00 ± 2.11	0.00 ± 2.07
Sx (mm)	2.25 ± 1.01 **	1.72 ± 0.66 +	1.66 ± 0.68
Sr (mm)	1.13 ± 0.52 **	0.86 ± 0.35	0.84 ± 0.36
Sl (mm)	1.12 ± 0.52 **	0.86 ± 0.33 +	0.82 ± 0.34
Sy (mm)	1.85 ± 0.73 **	1.50 ± 0.57	1.48 ± 0.63
Sa (mm)	0.93 ± 0.38 **	0.76 ± 0.30 +	0.73 ± 0.29
Sp (mm)	0.92 ± 0.37 **	0.74 ± 0.29	0.75 ± 0.38
TL (mm)	141.4 ± 53.0 **	231.1 ± 115.5 +	224.6 ± 111.5
TLx (mm)	91.7 ± 39.2 **	134.3 ± 66.2 +	129.5 ± 63.4
TLy (mm)	86.1 ± 30.6 **	144.2 ± 83.4	141.0 ± 81.6
Vm (mm/s)	7.10 ± 2.66 **	11.6 ± 5.80 +	11.3 ± 5.59
Vxm (mm/s)	4.60 ± 1.97 **	6.74 ± 3.32 +	6.50 ± 3.18
Vym (mm/s)	4.32 ± 1.54 **	7.24 ± 4.18	7.08 ± 4.09
Ay (°)	12.7 ± 36.0 **	-17.4 ± 37.0	-17.6 ± 37.5

** significantly ($p<0.01$) greater or less than frequencies 1595Hz and 2916Hz.
+ significantly ($p<0.05$) greater than frequency 2916Hz.

Table 11.2 The influence of sound on the centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions, magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), total path length (TL), mediolateral (TLx) and anteroposterior (TLy) path lengths, mean velocity of sway (Vm), mediolateral (Vxm) and anteroposterior (Vym) sway velocities, and angle of sway from the sagittal plane (Ay) (mean ± SD).

Postural sway parameter	Velocity of head movement	
	0.2 m/s	1.0 m/s
X (mm)	3.30 ± 2.15	3.26 ± 2.18
Y (mm)	0.11 ± 2.18	0.16 ± 2.13
Sx (mm)	1.72 ± 0.69	2.03 ± 0.95 **
Sr (mm)	0.87 ± 0.37	1.02 ± 0.49 **
Sl (mm)	0.86 ± 0.35	1.01 ± 0.48 **
Sy (mm)	1.42 ± 0.53	1.80 ± 0.74 **
Sa (mm)	0.71 ± 0.27	0.90 ± 0.37 **
Sp (mm)	0.71 ± 0.28	0.90 ± 0.40 **
TL (mm)	185.9 ± 106.4	212.2 ± 103.5 **
TLx (mm)	110.8 ± 60.4	126.2 ± 59.8 **
TLy (mm)	114.7 ± 74.1	132.8 ± 73.8 **
Vm (mm/s)	9.33 ± 5.34	10.6 ± 5.19 **
Vxm (mm/s)	5.56 ± 3.03	6.33 ± 3.00 **
Vym (mm/s)	5.76 ± 3.72	6.66 ± 3.70 **
Ay (°)	-8.47 ± 41.9	-6.43 ± 36.9 **

** significantly ($p<0.01$) greater or less than velocity 0.2m/s.

Table 11.3 The influence of the velocity of head movement on the centre of gravity projection in the mediolateral (X) and anteroposterior (Y) directions, magnitude of mediolateral (Sx) (separately to the right (Sr) and left (Sl)) and anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)), total path length (TL), mediolateral (TLx) and anteroposterior (TLy) path lengths, mean velocity of sway (Vm), mediolateral (Vxm) and anteroposterior (Vym) sway velocities, and angle of sway from the sagittal plane (Ay) (mean ± SD).

Direction of head movement

The direction of head movement had a significant influence on most postural sway parameters. There was no difference in X and Ay with either horizontal, vertical or diagonal head movement, however there was a significant ($p<0.01$) posterior shift in the COG projection with horizontal head movement with neck flexion compared with extension and neutral. There was no difference in Y for either vertical or diagonal head movement. Furthermore, there was no difference in Y between diagonal head movement and horizontal or vertical head movements (Table 11.4).

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
Y (mm)	0.22 ± 2.16	0.36 ± 2.28	0.03 ± 2.20 **

** significantly (p<0.01) less than extension and neutral.

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
Y (mm)	0.13 ± 2.06	0.03 ± 2.07	0.08 ± 2.13

Postural sway parameter	Diagonal head movement	
	LE	RE
Y (mm)	0.16 ± 2.17	0.08 ± 2.17

Table 11.4 **The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the anteroposterior centre of gravity projection (Y) (mean ± SD).**

As shown in Table 11.5 there was a significant (p<0.01) decrease in Sx, Sr and Sl with horizontal head movement with neck flexion compared with extension. In addition, there was a significant decrease in Sx, due to the significant reduction in Sl with the neck neutral compared with extension. For vertical head movement there was a significant increase in Sx, Sr and Sl with rotation either to the right or left compared with looking directly ahead. There were no differences in Sx, Sr and Sl for diagonal head movements. A significant (p<0.01) decrease in Sx, Sr and Sl was observed with the neck LE diagonal head movement compared with horizontal head movement with neck extension. No differences in Sx, Sr and Sl were observed between diagonal head movement with any neck position and vertical movement with any neck position.

Table 11.6 presents the findings for anteroposterior sway. There was a significant decrease in Sy, Sa and Sp with horizontal head movement with the neck in neutral and flexed compared with extension. For vertical head movement there was a significant decrease in Sy (p<0.01), Sa and Sp (p<0.01) with rotation to the right and left compared with looking directly ahead. There were no differences in

Sy, Sa and Sp for diagonal head movements. There was a significant ($p<0.01$) increase in Sy, Sa and Sp for both diagonal head movements compared with horizontal head movement with flexion, but no difference in Sy, Sa or Sp with vertical head movement for any neck position.

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
Sx (mm)	2.10 ± 1.14	1.88 ± 1.06 *	1.74 ± 0.73 **
Sr (mm)	1.06 ± 0.59	0.96 ± 0.56	0.87 ± 0.38 **
Sl (mm)	1.04 ± 0.57	0.92 ± 0.51 *	0.87 ± 0.36 **

* p<0.05, ** p<0.01 significantly less than extension.

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
Sx (mm)	1.91 ± 0.72 **	1.76 ± 0.70	1.91 ± 0.74 *
Sr (mm)	0.96 ± 0.38 **	0.88 ± 0.36	0.95 ± 0.38 *
Sl (mm)	0.95 ± 0.36 *	0.88 ± 0.36	0.95 ± 0.40 *

* p<0.05, ** p<0.01 significantly greater than looking directly ahead.

Postural sway parameter	Diagonal head movement	
	LE	RE
Sx (mm)	1.91 ± 0.75 **	1.79 ± 0.74
Sr (mm)	0.95 ± 0.39 **	0.90 ± 0.39
Sl (mm)	0.95 ± 0.38 **	0.89 ± 0.38

** significantly ($p<0.01$) less than horizontal head movement with extension.

Table 11.5 The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of mediolateral sway (Sx) (separately to the right (Sr) and left (Sl)) (mean ± SD).

Postural sway parameter	Horizontal head movement		
	Extension	Neutral	Flexion
Sy (mm)	1.60 ± 0.71	1.42 ± 0.72 **	1.33 ± 0.54 **
Sa (mm)	0.78 ± 0.35	0.70 ± 0.32 **	0.67 ± 0.28 **
Sp (mm)	0.81 ± 0.38	0.72 ± 0.50 *	0.66 ± 0.28 **

* p<0.05, ** p<0.01 significantly less than extension.

Postural sway parameter	Vertical head movement		
	Left	Looking ahead	Right
Sy (mm)	1.68 ± 0.62 **	1.87 ± 0.75	1.70 ± 0.62 **
Sa (mm)	0.86 ± 0.34 *	0.93 ± 0.39	0.86 ± 0.33 *
Sp (mm)	0.82 ± 0.31 **	0.94 ± 0.38	0.84 ± 0.31 **

* p<0.05, ** p<0.01 significantly less than looking directly ahead.

Postural sway parameter	Diagonal head movement	
	LE	RE
Sy (mm)	1.71 ± 0.61 **	1.60 ± 0.61 **
Sa (mm)	0.86 ± 0.32 **	0.80 ± 0.33 **
Sp (mm)	0.85 ± 0.30 **	0.80 ± 0.30 **

** significantly (p<0.01) greater than horizontal head movement with flexion.

Table 11.6 **The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)) (mean ± SD).**

A significant ($p<0.01$) decrease in TL, TLx and TLy was observed with horizontal head movement with neck flexion compared with extension (Table 11.7). In addition, there was a significant ($p<0.01$) decrease in TL, due to the significant ($p<0.01$) decrease in TLy, with the neck neutral compared with extension. There was also a significant decrease in TL, this time due to TLx ($p<0.01$), with neck flexion compared with neutral. Vertical head movement showed a significant increase in TLx with rotation to the right ($p<0.01$) and left compared with looking directly ahead. Furthermore, there was a significant reduction ($p<0.01$) in TLy with rotation to the left compared with looking directly ahead. For diagonal head movements no differences was observed in path lengths. However, there was significant decrease in TL and TLx ($p<0.01$) for RE diagonal head movement compared with horizontal head movement with neck extension. In addition, a significant increase in TL, TLx and TLy was observed for all neck positions for diagonal head movement compared with horizontal head movement with neck flexion. Finally, there was a significant ($p<0.01$) increase in TL, TLx and TLy with LE diagonal head compared with vertical head movement with rotation to the left.

Postural sway parameter	**Horizontal head movement**		
	Extension	**Neutral**	**Flexion**
TL (mm)	210.8 ± 115.4	191.4 ± 113.7 **	180.8 ± 96.0 ** +
TLx (mm)	129.0 ± 67.7	119.3 ± 69.1	109.2 ± 52.0 ** ++
TLy (mm)	128.4 ± 81.4	113.0 ± 75.4 **	109.7 ± 69.5 **

** significantly ($p<0.01$) less than extension.
+ $p<0.05$, ++ $p<0.01$ significantly less than neutral.

Postural way parameter	**Vertical head movement**		
	Left	**Looking ahead**	**Right**
TL (mm)	198.5 ± 98.9	200.8 ± 104.1	203.4 ± 100.9
TLx (mm)	118.3 ± 55.8 *	110.7 ± 56.6	120.5 ± 57.5 **
TLy (mm)	123.8 ± 69.6 **	133.2 ± 75.7	127.6 ± 70.6

* $p<0.05$,** $p<0.01$ significantly greater or less than looking directly ahead.

Postural sway parameter	**Diagonal head movement**	
	LE * **	**RE *** **
TL (mm)	210.6 ± 117.2 ++	195.9 ± 96.7 *
TLx (mm)	125.1 ± 67.0 ++	115.8 ± 55.3 **
TLy (mm)	131.7 ± 81.5 ++	122.7 ± 69.5

*** significantly ($p<0.01$) greater than horizontal head movement with flexion.
* $p<0.05$, ** $p<0.01$ significantly less than horizontal head movement with extension.
++ significantly ($p<0.01$) greater than vertical head movement with rotation to the left.

Table 11.7 **The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the total path length (TL) and path length in the mediolateral (TLx) and anteroposterior (TLy) directions (mean ± SD).**

Table 11.8 shows that the differences observed for the velocity of sway were similar to those with respect to path length, except for there being no difference between diagonal and vertical head movements.

Postural sway parameter	**Horizontal head movement**		
	Extension	**Neutral**	**Flexion**
Vm (mm/s)	10.6 ± 5.79	9.61 ± 5.70 **	9.07 ± 4.82 ** +
Vxm (mm/s)	6.47 ± 3.40	5.99 ± 3.47	5.48 ± 2.61 ** ++
Vym (mm/s)	6.44 ± 4.08	5.67 ± 3.78 **	5.50 ± 3.49 **

** significantly ($p<0.01$) less than extension.
+ $p<0.05$, ++ $p<0.01$ significantly less than neutral.

Postural sway parameter	**Vertical head movement**		
	Left	**Looking ahead**	**Right**
Vm (mm/s)	9.96 ± 4.96	10.1 ± 5.22	10.2 ± 5.06
Vxm (mm/s)	5.94 ± 2.80 *	5.56 ± 2.84	6.04 ± 2.89 **
Vym (mm/s)	6.21 ± 3.49 **	6.69 ± 3.80	6.40 ± 3.54

* $p<0.05$,** $p<0.01$ significantly greater or less than looking directly ahead.

Postural sway parameter	**Diagonal head movement**	
	LE ***	**RE** ***
Vm (mm/s)	10.6 ± 5.88	9.83 ± 4.85 *
Vxm (mm/s)	6.28 ± 3.36	5.81 ± 2.77 **
Vym (mm/s)	6.61 ± 4.09	6.16 ± 3.49

*** significantly ($p<0.01$) greater than horizontal head movement with flexion.
* $p<0.05$, ** $p<0.01$ significantly less than horizontal head movement with extension.

Table 11.8 The effect of horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the mean velocity of sway (Vm) and mean sway velocity in the mediolateral (Vxm) and anteroposterior (Vym) directions (mean ± SD).

Interaction between sound and velocity of head movement

The analyses of variance showed significant ($p<0.01$) interactions between sound and the velocity of head movement for Sx, Sr, Sl, Sy, Sa, Sp, TLx and Vxm. Although the initial analysis of variance showed a significant sound-velocity of head movement interaction, the differences were between inappropriate comparisons, i.e. no sound at the lower velocity compared with 1595Hz at the higher velocity.

Interaction between sound and direction of head movement

A significant interaction between sound and the direction of head movement for most postural sway parameters was observed, except for X, Sp and Ay. There was a significant interaction between sound and horizontal, but not vertical or diagonal, head movements for the anteroposterior COG projection (Table 11.9).

Postural sway parameter	Frequency	Horizontal head movement		
		Extension	Neutral	Flexion
Y (mm)	No sound	0.57 ± 2.35 **	0.78 ± 2.50 **	0.22 ± 2.32
	1595 Hz	0.00 ± 2.12 ++	0.24 ± 2.21	-0.03 ± 2.22 ++
	2916 Hz	0.09 ± 2.00 **	0.06 ± 2.09	-0.10 ± 2.09

** significantly ($p<0.01$) greater than flexion.
++ significantly ($p<0.01$) less than neutral.

Postural sway parameter	Frequency	Vertical head movement		
		Left	Looking ahead	Right
Y (mm)	No sound	0.25 ± 2.11	0.38 ± 2.23	0.23 ± 2.19
	1595 Hz	0.08 ± 2.11	-0.08 ± 2.10	-0.03 ± 2.06
	2916 Hz	0.06 ± 2.00	-0.19 ± 1.89	0.04 ± 2.18

Postural sway parameter	Frequency	Diagonal head movement	
		LE	RE
Y (mm)	No sound	0.49 ± 2.12	0.42 ± 2.29
	1595 Hz	-0.05 ± 2.11	-0.13 ± 2.04
	2916 Hz	0.05 ± 2.28	-0.04 ± 2.19

Table 11.9 **The interaction between sound and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the anteroposterior centre of gravity projection (Y) (mean ± SD).**

Without sound (Table 11.9) there was a significant ($p<0.01$) anterior shift of the COG projection with neck extension and neutral compared with flexion. At 1595Hz there was a significant ($p<0.01$) posterior shift of the COG projection with neck extension or flexion compared with neutral, while at 2916Hz there was a significant ($p<0.01$) anterior shift of the COG projection with neck extension compared with flexion. No differences in Y were observed between diagonal head movements and horizontal or vertical head movements for any sound condition.

As shown in Table 11.10 for horizontal head movement with no sound there was a significant increase in Sx, Sr and Sl with neck extension ($p<0.01$) and neutral compared with flexion. At 1595Hz there was a significant increase in Sx, Sr and Sl with neck extension compared with flexion, while at 2916Hz a significant increase in Sx, Sr and Sl with neck extension was observed compared with neutral and flexion. For vertical head movement (Table 11.10) without sound and at 2916Hz no significant differences in Sx, Sr or Sl were observed. In contrast, at 1595Hz there was a significant ($p<0.01$) decrease in Sx, Sr and Sl when looking directly ahead compared with rotation to the left. In addition, a significant ($p<0.01$) decrease in Sx, due to a significant ($p<0.01$) decrease Sl, was observed with rotation to the right compared with rotation to the left. Diagonal head movements (Table 11.10) showed no differences in Sx, Sr and Sl for any sound condition. However, without sound there was a significant reduction in Sx ($p<0.01$), Sr and Sl ($p<0.01$) for both diagonal head movements compared with horizontal head movement with neck extension. There was no difference between diagonal and horizontal head movements at 1595Hz and 2916Hz. No differences were observed between head movement diagonally and vertically for any sound condition.

Table 11.11 shows that for horizontal head movement with no sound there was a significant ($p<0.01$) increase in Sy and Sa with neck extension compared with flexion. Furthermore, there was a significant increase in Sy with the neck neutral compared with flexion. At both 1595Hz and 2916Hz a significant increase in Sy and Sa with neck extension compared with flexion was also observed. In addition, at 2916Hz there was a significant ($p<0.01$) increase in Sa with neck extension compared with neutral.

Postural sway parameter	Frequency	Horizontal head movement		
		Extension	Neutral	Flexion
Sx (mm)	No sound	2.62 ± 1.39 **	2.48 ± 1.32 *	2.07 ± 0.87
	1595 Hz	0.91 ± 0.39 *	0.86 ± 0.45	0.80 ± 0.33
	2916 Hz	1.87 ± 1.03 * ++	1.46 ± 0.62	1.55 ± 0.58
Sr (mm)	No sound	1.32 ± 0.70 **	1.27 ± 0.70 *	1.04 ± 0.45
	1595 Hz	0.90 ± 0.37 *	0.85 ± 0.40	0.80 ± 0.27
	2916 Hz	0.94 ± 0.55 * +	0.74 ± 0.34	0.77 ± 0.29
Sl (mm)	No sound	1.30 ± 0.72 **	1.21 ± 0.65 *	1.03 ± 0.43
	1595 Hz	1.48 ± 0.60 *	1.29 ± 0.49	1.25 ± 0.50
	2916 Hz	0.93 ± 0.49 * ++	0.72 ± 0.29	0.78 ± 0.31

* $p<0.05$, ** $p<0.01$ significantly greater than flexion.
+ $p<0.05$, ++ $p<0.01$ significantly greater than neutral.

Postural sway parameter	Frequency	Vertical head movement		
		Left	Looking ahead	Right
Sx (mm)	No sound	2.23 ± 0.82	2.09 ± 0.82	2.32 ± 0.83
	1595 Hz	1.83 ± 0.60	1.57 ± 0.54 **	1.67 ± 0.55 **
	2916 Hz	1.68 ± 0.62	1.62 ± 0.59	1.73 ± 0.64
Sr (mm)	No sound	1.11 ± 0.44	1.03 ± 0.40	1.14 ± 0.42
	1595 Hz	0.91 ± 0.31	0.78 ± 0.27 **	0.85 ± 0.31
	2916 Hz	0.86 ± 0.33	0.83 ± 0.34	0.86 ± 0.34
Sl (mm)	No sound	1.12 ± 0.41	1.06 ± 0.44	1.18 ± 0.50
	1595 Hz	0.92 ± 0.30	0.79 ± 0.28 **	0.81 ± 0.26 **
	2916 Hz	0.82 ± 0.30	0.79 ± 0.27	0.86 ± 0.32

** significantly ($p<0.01$) less than rotation to the left.

Postural sway parameter	Frequency	Diagonal head movement	
		LE	RE
Sx (mm)	No sound	2.06 ± 0.80	2.09 ± 0.96
	1595 Hz	1.89 ± 0.75	1.70 ± 0.55
	2916 Hz	1.77 ± 0.68	1.59 ± 0.56
Sr (mm)	No sound	1.04 ± 0.42	1.05 ± 0.49
	1595 Hz	0.94 ± 0.36	0.84 ± 0.29
	2916 Hz	0.88 ± 0.36	0.81 ± 0.30
Sl (mm)	No sound	1.03 ± 0.40	1.04 ± 0.49
	1595 Hz	0.95 ± 0.40	0.86 ± 0.30
	2916 Hz	0.89 ± 0.34	0.78 ± 0.29

Table 11.10 The interaction between sound and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of mediolateral sway (Sx) (separately to the right (Sr) and left (Sl)) (mean ± SD).

Postural sway parameter	Frequency	Horizontal head movement		
		Extension	Neutral	Flexion
Sy (mm)	No sound	1.91 ± 0.88 **	1.73 ± 0.72 *	1.49 ± 0.63
	1595 Hz	1.48 ± 0.60 **	1.29 ± 0.49	1.25 ± 0.50
	2916 Hz	1.40 ± 0.49 **	1.24 ± 0.82	1.24 ± 0.44
Sa (mm)	No sound	0.92 ± 0.44 **	0.87 ± 0.39	0.76 ± 0.31
	1595 Hz	0.74 ± 0.31 *	0.65 ± 0.28	0.64 ± 0.28
	2916 Hz	0.70 ± 0.24 ** ++	0.57 ± 0.19	0.61 ± 0.22

* p<0.05, ** p<0.01 significantly greater than flexion.
++ significantly (p<0.01) greater than neutral.

Postural sway parameter	Frequency	Vertical head movement		
		Left	Looking ahead	Right
Sy (mm)	No sound	1.97 ± 0.69 **	2.22 ± 0.88	1.93 ± 0.62 **
	1595 Hz	1.56 ± 0.48 *	1.72 ± 0.62	1.54 ± 0.49 *
	2916 Hz	1.50 ± 0.59	1.66 ± 0.59	1.63 ± 0.69
Sa (mm)	No sound	1.02 ± 0.40	1.10 ± 0.44	1.00 ± 0.34 *
	1595 Hz	0.80 ± 0.26	0.87 ± 0.34	0.77 ± 0.25 *
	2916 Hz	0.76 ± 0.31	0.83 ± 0.31	0.81 ± 0.34

* p<0.05 ** p<0.01 significantly less than looking directly ahead.

Postural sway parameter	Frequency	Diagonal head movement	
		LE	RE
Sy (mm)	No sound	1.77 ± 0.53	1.83 ± 0.67
	1595 Hz	1.72 ± 0.65	1.46 ± 0.56
	2916 Hz	1.63 ± 0.65	1.51 ± 0.55
Sa (mm)	No sound	0.90 ± 0.29	0.92 ± 0.36
	1595 Hz	0.85 ± 0.34	0.72 ± 0.31
	2916 Hz	0.81 ± 0.34	0.75 ± 0.28

Table 11.11 The interaction between sound and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of anteroposterior sway (Sy) (separately anteriorly (Sa)) (mean ± SD).

For vertical head movement (Table 11.11) there was a significant decrease in Sy with rotation either to the right or left compared with looking directly ahead without sound (p<0.01) and at 1595Hz. Similarly, there was a significant decrease in Sa with rotation to the right compared with looking directly ahead. No differences in Sy or Sa were observed at 2916Hz.

No differences were observed in Sy or Sa for diagonal head movement with any sound condition (Table 11.11). However, there was a significant ($p<0.01$) increase in Sy and Sa with both diagonal head movements without sound and at 2916Hz compared with horizontal head movement with neck flexion. Furthermore, at 1595Hz a significant ($p<0.01$) increase in Sy and Sa was observed with LE diagonal head movement compared with horizontal head movement with neck flexion. No differences were observed between head movement diagonally and vertically for any sound condition.

As shown in Table 11.12 for horizontal head movement without sound there were significant increases in TL, TLx and TLy with neck extension ($p<0.01$) or neutral compared with flexion. At 1595Hz there was a significant increase ($p<0.01$) in TL, TLx and TLy with neck extension compared with flexion, while at 2916Hz there was a significant ($p<0.01$) increase in TL, TLx and TLy with neck extension compared with neutral and flexion. In addition, there was a significant ($p<0.01$) increase in TLy with neck flexion compared with neutral.

For vertical head movement (Table 11.12) there were no differences in TL, TLx and TLy for any neck position without sound or at 2916Hz. However, at 1595Hz there was a significant increase in TLx with rotation to the right and left compared with looking directly ahead. In contrast, there was a significant decrease in TLy with rotation to the right ($p<0.01$) and left compared with looking directly ahead. The increase in TLx and the decrease in TLy did not significantly change TL.

There were no differences in TL, TLx and TLy for diagonal head movement with any sound condition (Table 11.12). Without sound there was a significant ($p<0.01$) decrease in TL, TLx and TLy with both diagonal head movements compared with horizontal head movement with neck extension. In addition, at 1595Hz a significant increase in TL ($p<0.01$), TLx and TLy ($p<0.01$) was observed with LE diagonal head movement with compared with horizontal head movement with neck flexion. At 2916Hz there was a significant ($p<0.01$) increase in TL, TLx and TLy with both diagonal head movements compared with

Postural sway parameter	Frequency	Horizontal head movement		
		Extension	Neutral	Flexion
TL (mm)	No sound	161.6 ± 71.03 **	151.5 ± 69.57 *	128.9 ± 41.9
	1595 Hz	237.6 ± 128.89 **	225.4 ± 142.9	211.5 ± 111.5
	2916 Hz	233.3 ± 123.31 ** ++	197.4 ± 106.1	202.0 ± 98.5
TLx (mm)	No sound	107.7 ± 53.32 **	102.7 ± 52.74 *	86.0 ± 30.2
	1595 Hz	140.8 ± 71.71 **	137.9 ± 86.9	125.0 ± 60.7
	2916 Hz	138.5 ± 72.79 ** ++	117.2 ± 59.8	116.5 ± 52.6
TLy (mm)	No sound	95.8 ± 40.34 **	87.7 ± 36.19 *	76.0 ± 24.7
	1595 Hz	145.9 ± 94.53 **	132.9 ± 96.0	128.5 ± 81.7
	2916 Hz	143.5 ± 89.30 ** ++	118.5 ± 75.6 **	124.6 ± 75.5

* $p<0.05$, ** $p<0.01$ significantly greater or less than flexion.
++ significantly ($p<0.01$) greater than neutral.

Postural sway parameter	Frequency	Vertical head movement		
		Left	Looking ahead	Right
TL (mm)	No sound	140.6 ± 44.9	140.6 ± 48.0	144.2 ± 47.0
	1595 Hz	230.4 ± 102.4	233.4 ± 115.3	229.5 ± 103.3
	2916 Hz	224.6 ± 110.0	228.4 ± 108.7	236.6 ± 112.8
TLx (mm)	No sound	89.6 ± 32.5	85.1 ± 33.1	92.9 ± 34.2
	1595 Hz	135.5 ± 57.7 *	122.7 ± 62.7	132.0 ± 59.2 *
	2916 Hz	129.9 ± 61.7	124.4 ± 61.1	136.5 ± 65.1
TLy (mm)	No sound	87.5 ± 26.9	91.4 ± 31.4	88.4 ± 27.5
	1595 Hz	142.8 ± 74.2 *	158.2 ± 86.2	145.2 ± 75.7 **
	2916 Hz	141.0 ± 80.7	150.1 ± 79.5	149.2 ± 79.5

* $p< 0.05$, ** $p<0.01$ significantly greater or less than looking directly ahead.

Postural sway parameter	Frequency	Diagonal head movement	
		LE	RE
TL (mm)	No sound	130.5 ± 44.3	133.4 ± 44.2
	1595 Hz	251.9 ± 120.2	228.8 ± 98.4
	2916 Hz	249.3 ± 124.9	225.5 ± 104.1
TLx (mm)	No sound	85.2 ± 32.8	84.6 ± 32.3
	1595 Hz	146.0 ± 70.9	134.4 ± 56.4
	2916 Hz	144.2 ± 71.6	128.5 ± 59.7
TLy (mm)	No sound	78.8 ± 24.8	83.2 ± 26.6
	1595 Hz	159.0 ± 83.5	141.1 ± 73.6
	2916 Hz	157.5 ± 91.3	143.8 ± 78.7

Table 11.12 The interaction between sound and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the total path length (TL) and path length in the mediolateral (TLx) and anteroposterior (TLy) directions (mean ± SD).

Postural sway parameter	Frequency	Horizontal head movement		
		Extension	Neutral	Flexion
Vm (mm/s)	No sound	8.11 ± 3.56 **	7.60 ± 3.49 *	6.47 ± 2.10
	1595 Hz	11.9 ± 6.47 **	11.3 ± 7.17	10.6 ± 5.59
	2916 Hz	11.7 ± 6.19 ** ++	9.91 ± 5.33	10.1 ± 4.94
Vxm (mm/s)	No sound	5.41 ± 2.68 **	5.15 ± 2.65 *	4.31 ± 1.51
	1595 Hz	7.06 ± 3.60 **	6.92 ± 4.36	6.27 ± 3.05
	2916 Hz	6.95 ± 3.65 ** ++	5.88 ± 3.00	5.85 ± 2.64
Vym (mm/s)	No sound	4.80 ± 2.02 **	4.40 ± 1.82 *	3.81 ± 1.24
	1595 Hz	7.32 ± 4.74 **	6.67 ± 4.82	6.45 ± 4.10
	2916 Hz	7.20 ± 4.48 ** ++	5.95 ± 3.79 **	6.25 ± 3.79

* p<0.05, ** p<0.01 significantly greater or less than flexion.
++ significantly (p<0.01) greater than neutral.

Postural sway parameter	Frequency	Vertical head movement		
		Left	Looking ahead	Right
Vm (mm/s)	No sound	7.05 ± 2.25	7.05 ± 2.41	7.24 ± 2.36
	1595 Hz	11.6 ± 5.14	11.7 ± 5.78	11.5 ± 5.18
	2916 Hz	11.3 ± 5.52	11.5 ± 5.45	11.9 ± 5.66
Vxm (mm/s)	No sound	4.50 ± 1.63	4.27 ± 1.66	4.66 ± 1.72
	1595 Hz	6.80 ± 2.90 *	6.16 ± 3.15	6.62 ± 2.97 *
	2916 Hz	6.52 ± 3.09	6.24 ± 3.07	6.85 ± 3.26
Vym (mm/s)	No sound	4.39 ± 1.35	4.58 ± 1.58	4.44 ± 1.38
	1595 Hz	7.17 ± 3.72 *	7.94 ± 4.32	7.29 ± 3.80 **
	2916 Hz	7.07 ± 4.05	7.53 ± 3.99	7.48 ± 3.99

* p< 0.05, ** p<0.01 significantly greater or less than looking directly ahead.

Postural sway parameter	Frequency	Diagonal head movement	
		LE	RE
Vm (mm/s)	No sound	6.55 ± 2.22	6.69 ± 2.22
	1595 Hz	12.6 ± 6.03	11.5 ± 4.94
	2916 Hz	12.5 ± 6.26	11.3 ± 5.22
Vxm (mm/s)	No sound	4.28 ± 1.64	4.25 ± 1.62
	1595 Hz	7.33 ± 3.56	6.74 ± 2.83
	2916 Hz	7.23 ± 3.59	6.45 ± 2.99
Vym (mm/s)	No sound	3.95 ± 1.25	4.17 ± 1.33
	1595 Hz	7.98 ± 4.19	7.08 ± 3.69
	2916 Hz	7.90 ± 4.58	7.21 ± 3.95

Table 11.13 The interaction between sound and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the mean velocity of sway (Vm) and velocity of sway in the mediolateral (Vxm) and anteroposterior (Vym) directions (mean ± SD).

horizontal head movement with neck flexion. Comparing diagonal with vertical head movements the data shows differences for the without sound condition only. There was a significant reduction in TL with LE diagonal head movement, due to a significant ($p<0.01$) decrease in TLy, compared with vertical head movement with rotation to the right and left.

As shown in Table 11.13 the differences observed for the mean velocity of sway, as well as for the velocity of sway in both the mediolateral and anteroposterior directions, were similar to those observed for path length.

Interaction between velocity and direction of head movement

The analyses of variance showed a significant interaction between the velocity and direction of head movement for all anteroposterior sway parameters except the mean anteroposterior COG position. For horizontal head movement at 0.2m/s there was a significant ($p<0.01$) increase in Sy, Sa and Sp with neck extension compared with flexion and neutral (Table 11.14). At 1.0m/s there was a significant ($p<0.01$) increase in Sy, Sa and Sp with neck extension compared with flexion. In addition, there was also a significant ($p<0.01$) decrease in Sy, due to a significant decrease in Sa, with neck flexion compared with neutral.

For vertical head movement (Table 11.14) at the lower velocity there were no differences in Sy, Sa or Sp irrespective of neck flexion/extension. However, at the higher velocity there were significant ($p<0.01$) decreases in Sy, Sa and Sp with rotation to the right and left compared with looking directly ahead.

No differences were observed in Sy, Sa or Sp with diagonal head movement irrespective of the velocity of movement (Table 11.14). At 0.2m/s there was a significant ($p<0.01$) increase in Sy, due to significant ($p<0.01$) increase in Sa and Sp, with LE diagonal head movement and a significant increase in Sy, due to significant ($p<0.01$) increase in Sp, with RE diagonal head movement compared with horizontal head movement with neck flexion. In addition, at 1.0m/s a significant ($p<0.01$) increase Sy, Sa and Sp was observed with both diagonal head movements compared with horizontal head movement with neck flexion.

Comparing diagonal with vertical head movements, the only difference observed was at the lower velocity where there was a significant increase in Sy, due to a significant (p<0.01) increase in Sp, for LE diagonal head movement compared with vertical head movement with rotation to the left.

Postural sway parameter	Velocity of head movement	Horizontal head movement		
		Extension	Neutral	Flexion
Sy (mm)	0.2 m/s	1.54 ± 0.66 **	1.26 ± 0.48	1.27 ± 0.48
	1.0 m/s	1.66 ± 0.75 ++	1.58 ± 0.87 ++	1.39 ± 0.59
Sa (mm)	0.2 m/s	0.75 ± 0.32 **	0.62 ± 0.24	0.65 ± 0.25
	1.0 m/s	0.82 ± 0.38 ++	0.77 ± 0.37 +	0.70 ± 0.30
Sp (mm)	0.2 m/s	0.78 ± 0.36 **	0.63 ± 0.28	0.62 ± 0.25
	1.0 m/s	0.84 ± 0.40 ++	0.81 ± 0.64	0.69 ± 0.31

** significantly (p<0.01) greater than neutral and flexion.
+ p<0.05, ++ p<0.01 significantly greater than flexion.

Postural sway parameter	Velocity of head movement	Vertical head movement		
		Left	Looking ahead	Right
Sy (mm)	0.2 m/s	1.44 ± 0.48	1.46 ± 0.43	1.49 ± 0.57
	1.0 m/s	1.92 ± 0.67 **	2.28 ± 0.77	1.90 ± 0.61 **
Sa (mm)	0.2 m/s	0.74 ± 0.28	0.72 ± 0.23	0.75 ± 0.28
	1.0 m/s	0.98 ± 0.36 **	1.14 ± 0.40	0.97 ± 0.33 *
Sp (mm)	0.2 m/s	0.69 ± 0.23	0.73 ± 0.21	0.74 ± 0.29
	1.0 m/s	0.94 ± 0.33 **	1.14 ± 0.40	0.93 ± 0.30 **

* p<0.05, ** p<0.01 significantly less than looking direction ahead.

Postural sway parameter	Velocity of head movement	Diagonal head movement	
		LE	RE
Sy (mm)	0.2 m/s	1.54 ± 0.58	1.39 ± 0.48
	1.0 m/s	1.87 ± 0.60	1.81 ± 0.66
Sa (mm)	0.2 m/s	0.77 ± 0.31	0.68 ± 0.24
	1.0 m/s	0.94 ± 0.32	0.91 ± 0.36
Sp (mm)	0.2 m/s	0.77 ± 0.30	0.70 ± 0.25
	1.0 m/s	0.93 ± 0.29	0.90 ± 0.32

Table 11.14 The interaction between velocity of head movement and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of anteroposterior sway (Sy) (separately anteriorly (Sa) and posteriorly (Sp)) (mean ± SD).

For horizontal head movement at both 0.2m/s and 1.0m/s there were significant ($p<0.01$) increases in TLy and Vym with neck extension compared with flexion and neutral (Table 11.15). For vertical head movement at the lower velocity no differences in TLy and Vym were observed. However, at the higher velocity there were significant ($p<0.01$) reductions in TLy and Vym with rotation to the right and left compared with looking directly ahead.

Postural sway parameter	Velocity of head movement	Horizontal head movement		
		Extension	Neutral	Flexion
TLy (mm)	0.2 m/s	122.5 ± 81.4 **	108.0 ± 78.5	106.2 ± 71.1
	1.0 m/s	134.3 ± 81.5 **	118.1 ± 72.5	113.1 ± 68.3
Vym (mm/s)	0.2 m/s	6.14 ± 4.09 **	5.42 ± 3.94	5.33 ± 3.57
	1.0 m/s	6.74 ± 4.10 **	5.92 ± 3.64	5.68 ± 3.43

** significantly ($p<0.01$) greater than neutral and flexion.

Postural sway parameter	Velocity of head movement	Vertical head movement		
		Left	Looking ahead	Right
TLy (mm)	0.2 m/s	112.3 ± 66.1	115.2 ± 75.3	117.0 ± 71.5
	1.0 m/s	135.2 ± 71.7 **	151.3 ± 72.2	138.2 ± 68.5 **
Vym (mm/s)	0.2 m/s	5.64 ± 3.32	5.78 ± 3.78	5.87 ± 3.59
	1.0 m/s	6.78 ± 3.60 **	7.59 ± 3.62	6.93 ± 3.44 **

** significantly ($p<0.01$) less than looking directly ahead.

Postural sway parameter	Velocity of head movement	Diagonal head movement	
		LE	RE
TLy (mm)	0.2 m/s	123.6 ± 82.6	113.0 ± 66.5
	1.0 m/s	139.8 ± 80.2	132.4 ± 71.6
Vym (mm/s)	0.2 m/s	6.20 ± 4.15	5.67 ± 3.34
	1.0 m/s	7.02 ± 4.02	6.64 ± 3.59

Table 11.15 The interaction between velocity of head movement and horizontal head movement with the neck extended, in neutral and flexed, vertical movement with rotation to the left, looking directly ahead and rotation to the right and diagonal movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the path length and velocity of sway in the anteroposterior (TLy and Vym) direction (mean ± SD).

No differences were observed in TLy and Vym for diagonal head movement at either velocity (Table 11.15). At the lower velocity there was a significant increase in TLy and Vym for RE diagonal head movement and significant ($p<0.01$) increases in TLy and Vym for LE diagonal movement compared with horizontal head movement with neck flexion. Furthermore, at the higher velocity a significant increase ($p<0.01$) in TLy and Vym was observed for both diagonal head movements compared with horizontal head movement with neck flexion.

Interaction between sound, velocity and direction of head movement

Significant interactions between sound, velocity and direction of head movement were observed for the magnitude of mediolateral sway, total path length and mean velocity of sway, as well as the mediolateral and anteroposterior direction for both latter parameters. As shown in Table 11.16 for horizontal head movement at 0.2m/s without sound there were significant increases in Sx ($p<0.01$), Sr ($p<0.01$) and Sl with neck extension compared with neutral and flexion. Furthermore, at 1.0m/s there were significant increases in Sx, Sr and Sl with neck extension and neutral (Sx and Sr, $p<0.01$) compared with flexion. At 1595Hz and at 0.2m/s there was a significant increase in Sx, due to the significant ($p<0.01$) increase in Sr, with neck extension compared with flexion. At 2916Hz there were no differences in Sx, Sr and Sl at the lower velocity, however at the higher velocity there was a significant increase in Sx, Sr and Sl with neck extension compared with flexion. In addition, Sx was significantly greater, due to the significant increase in Sr, in neck extension than in neutral.

For vertical head movement (Table 11.17) there were no differences in Sx, Sr and Sl with neck rotation either without sound or at 2916Hz for either velocity. However, as shown in Table 11.17 at 1595Hz at the lower velocity there was a significant ($p<0.01$) increase in Sx, Sr and Sl with rotation to the left compared with looking directly ahead. In addition, Sx was significantly greater, due to the significant ($p<0.01$) increase in Sl, with rotation to the left than to the right. No significant differences were observed in Sx, Sr or Sl at 1595Hz at the higher velocity.

No sound

Postural sway parameter	Velocity of head movement	Horizontal head movement		
		Extension	Neutral	Flexion
Sx (mm)	0.2 m/s	2.32 ± 0.85 **	1.84 ± 0.67	1.85 ± 0.66
	1.0 m/s	2.92 ± 1.74 +	3.12 ± 1.51 ++	2.30 ± 1.00
Sr (mm)	0.2 m/s	1.18 ± 0.42 **	0.94 ± 0.36	0.94 ± 0.37
	1.0 m/s	1.46 ± 0.89 +	1.60 ± 0.79 ++	1.15 ± 0.89
Sl (mm)	0.2 m/s	1.15 ± 0.48 *	0.90 ± 0.35	0.91 ± 0.30
	1.0 m/s	1.46 ± 0.88 +	1.51 ± 0.74 +	1.15 ± 0.51

** significantly (p<0.01) greater than neutral and flexion.
+ p<0.05, ++ p<0.01 significantly greater than flexion.

Frequency 1595 Hz

Postural sway parameter	Velocity of head movement	Horizontal head movement		
		Extension	Neutral	Flexion
Sx (mm)	0.2 m/s	1.73 ± 0.68 +	1.66 ± 0.99	1.55 ± 0.57
	1.0 m/s	1.89 ± 0.82	1.75 ± 0.67	1.64 ± 0.62
Sr (mm)	0.2 m/s	0.88 ± 0.35 ++	0.84 ± 0.53	0.78 ± 0.32
	1.0 m/s	0.95 ± 0.43	0.87 ± 0.37	0.82 ± 0.43
Sl (mm)	0.2 m/s	0.85 ± 0.34	0.81 ± 0.46	0.77 ± 0.26
	1.0 m/s	0.94 ± 0.40	0.88 ± 0.32	0.82 ± 0.29

+ p<0.05, ++ p<0.01 significantly greater than flexion.

Frequency 2916 Hz

Postural sway parameter	Velocity of head movement	Horizontal head movement		
		Extension	Neutral	Flexion
Sx (mm)	0.2 m/s	0.80 ± 0.34	0.75 ± 0.38	0.77 ± 0.29
	1.0 m/s	1.07 ± 0.68 *	0.73 ± 0.29	0.77 ± 0.68
Sr (mm)	0.2 m/s	0.82 ± 0.33	0.73 ± 0.32	0.77 ± 0.30
	1.0 m/s	1.04 ± 0.60 *	0.71 ± 0.27	0.80 ± 0.32
Sl (mm)	0.2 m/s	1.30 ± 0.44	1.16 ± 0.43	1.20 ± 0.45
	1.0 m/s	1.51 ± 0.53 +	1.31 ± 1.08	1.29 ± 0.44

* significantly (p<0.05) greater than neutral and flexion.
+ significantly (p<0.05) greater than flexion.

Table 11.16 The interaction between sound, velocity and horizontal head movement with the neck extended, in neutral and flexed on the magnitude of mediolateral sway (Sx) (separately to the right (Sr) and left (Sl)) (mean ± SD).

No sound

Postural sway parameter	Velocity of head movement	Vertical head movement		
		Left	Looking ahead	Right
Sx (mm)	0.2 m/s	2.09 ± 0.79	1.81 ± 0.50	2.11 ± 0.79
	1.0 m/s	2.37 ± 0.85	2.37 ± 0.98	2.53 ± 0.84
Sr (mm)	0.2 m/s	1.06 ± 0.46	0.91 ± 0.28	1.00 ± 0.36
	1.0 m/s	1.16 ± 0.42	1.16 ± 0.47	1.28 ± 0.43
Sl (mm)	0.2 m/s	1.03 ± 0.36	0.91 ± 0.27	1.12 ± 0.55
	1.0 m/s	1.20 ± 0.45	1.21 ± 0.53	1.25 ± 0.44

Frequency 1595 Hz

Postural sway parameter	Velocity of head movement	Vertical head movement		
		Left	Looking ahead	Right
Sx (mm)	0.2 m/s	1.78 ± 0.64 **	1.47 ± 0.53	1.55 ± 0.54 +
	1.0 m/s	1.87 ± 0.56	1.67 ± 0.55	1.78 ± 0.55
Sr (mm)	0.2 m/s	0.88 ± 0.34 **	0.74 ± 0.29	0.79 ± 0.31
	1.0 m/s	0.93 ± 0.29	0.82 ± 0.26	0.92 ± 0.31
Sl (mm)	0.2 m/s	0.90 ± 0.32 **	0.74 ± 0.27	0.76 ± 0.24 ++
	1.0 m/s	0.94 ± 0.28	0.85 ± 0.30	0.87 ± 0.26

** significantly (p<0.01) greater than looking directly ahead.
+ p<0.05, ++ p<0.01 significantly less than rotation to the left.

Frequency 2916 Hz

Postural sway parameter	Velocity of head movement	Vertical head movement		
		Left	Looking ahead	Right
Sx (mm)	0.2 m/s	1.54 ± 0.59	1.52 ± 0.62	1.62 ± 0.58
	1.0 m/s	1.82 ± 0.62	1.73 ± 0.55	1.84 ± 0.69
Sr (mm)	0.2 m/s	0.79 ± 0.34	0.79 ± 0.37	0.82 ± 0.32
	1.0 m/s	0.93 ± 0.32	0.87 ± 0.30	0.91 ± 0.35
Sl (mm)	0.2 m/s	0.75 ± 0.27	0.73 ± 0.27	0.80 ± 0.26
	1.0 m/s	0.89 ± 0.32	0.86 ± 0.26	0.93 ± 0.36

Table 11.17 The interaction between sound, velocity and vertical head movement with looking directly ahead, rotation to the right or left on the magnitude of mediolateral sway (Sx) (separately to the right (Sr) and left (Sl)) (mean ± SD).

For diagonal head movements (Table 11.18) there were no differences in Sx, Sr and Sl for any neck position at either velocity of movement for any of the sound condition. Without sound and at the lower velocity there was a significant ($p<0.01$) decrease in Sx, Sr and Sl with both diagonal head movements compared with horizontal head movement with neck extension. In addition, a significant ($p<0.01$) reduction in Sx, due to the decrease in Sr, with LE diagonal head movement compared with vertical head movement with rotation to the left was observed. No differences in Sx, Sr and Sl were observed for diagonal head movement compared with horizontal or vertical head movement without sound at the higher velocity. There were also no differences in Sx, Sr and Sl with diagonal head movement compared with horizontal or vertical head movement at 1595Hz at either velocity. No differences in Sx, Sr and Sl with diagonal head movement compared with horizontal or vertical head movement were observed at 2916Hz at the lower velocity, however at the higher velocity there was a significant increase in Sx, due to the significant ($p<0.01$) increase in Sr with LE diagonal head movement compared with vertical head movement with rotation to the left. No differences were observed in Sx, Sr and Sl with diagonal head movement compared with horizontal head movement at 2916Hz at the higher velocity.

As shown in Table 11.19 for horizontal head movement at 0.2m/s and without sound there were significant ($p<0.01$) increases in TL, TLx and TLy with neck extension compared with neutral and flexion. Furthermore, at 1.0m/s there was a significant ($p<0.01$) increase in TL, TLx and TLy with neck extension and neutral compared with flexion. At 1595Hz at the lower velocity there was a significant increase in TL ($p<0.01$), TLx and TLy ($p<0.01$) with neck extension compared with flexion: there being no differences at the higher velocity. At 2916Hz and 0.2m/s movement there were significant increases in TL and TLy with the neck extension compared with flexion. Furthermore, TLy was significantly greater in neck extension than neutral. At 1.0m/s there were significant ($p<0.01$) increases in TL, TLx and TLy with neck extension compared with neutral and flexion. In addition, TLy was significantly greater in neck flexion than in neutral.

As shown in Table 11.20 for vertical head movement without sound no differences in TL, TLx and TLy were observed, while at 1595Hz at the lower velocity there were also no differences in TL, TLx and TLy. In contrast, at the higher velocity there was a significant decrease in TLy with rotation to the right and left ($p<0.01$) compared with looking directly ahead. The significant decrease in TLy with rotation to the left caused a significant decrease in TL with rotation to the left compared with looking directly ahead. At 2916Hz and the lower velocity there was a significant decrease in TL ($p<0.01$), TLx and TLy with rotation to the left compared with rotation to the right. Furthermore, there was a significant decrease in TL, due to the significant decrease in TLx, when looking directly ahead compared with rotation to the right. At the higher velocity at 2916Hz no significant differences in TL, TLx and TLy were observed.

No sound

Postural sway parameter	Velocity of head movement	Diagonal head movement	
		LE	RE
Sx (mm)	0.2 m/s	1.78 ± 0.64	1.81 ± 0.94
	1.0 m/s	2.35 ± 0.86	2.37 ± 0.92
Sr (mm)	0.2 m/s	0.88 ± 0.32	0.91 ± 0.53
	1.0 m/s	1.20 ± 0.46	1.19 ± 0.42
Sl (mm)	0.2 m/s	0.90 ± 0.34	0.90 ± 0.43
	1.0 m/s	1.15 ± 0.42	1.18 ± 0.51

Frequency 1595 Hz

Postural sway parameter	Velocity of head movement	Diagonal head movement	
		LE	RE
Sx (mm)	0.2 m/s	1.78 ± 0.71	1.63 ± 0.49
	1.0 m/s	2.00 ± 0.79	1.77 ± 0.61
Sr (mm)	0.2 m/s	0.89 ± 0.34	0.80 ± 0.23
	1.0 m/s	0.99 ± 0.38	0.88 ± 0.33
Sl (mm)	0.2 m/s	0.89 ± 0.38	0.83 ± 0.27
	1.0 m/s	1.00 ± 0.41	0.89 ± 0.32

Frequency 2916 Hz

Postural sway parameter	Velocity of head movement	Diagonal head movement	
		LE	RE
Sx (mm)	0.2 m/s	1.66 ± 0.60	1.59 ± 0.58
	1.0 m/s	1.88 ± 0.74	1.60 ± 0.56
Sr (mm)	0.2 m/s	0.81 ± 0.30	0.82 ± 0.32
	1.0 m/s	0.95 ± 0.41	0.80 ± 0.29
Sl (mm)	0.2 m/s	0.85 ± 0.32	0.77 ± 0.29
	1.0 m/s	0.93 ± 0.36	0.80 ± 0.30

Table 11.18 The interaction between sound, velocity and diagonal head movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the magnitude of mediolateral sway (Sx) (separately to the right (Sr) and left (Sl)) (mean ± SD).

No sound

Postural sway parameter	Velocity of head movement	Horizontal head movement		
		Extension	**Neutral**	**Flexion**
TL (mm)	0.2 m/s	145.1 ± 53.3 **	121.8 ± 37.1	121.0 ± 38.8
	1.0 m/s	178.2 ± 83.2 ++	181.2 ± 81.8 ++	136.8 ± 44.3
TLx (mm)	0.2 m/s	94.2 ± 35.1 **	78.7 ± 25.4	79.8 ± 27.9
	1.0 m/s	121.3 ± 64.9 ++	126.7 ± 62.0 ++	92.1 ± 31.7
TLy (mm)	0.2 m/s	88.6 ± 35.5 **	74.1 ± 24.0	71.9 ± 22.2
	1.0 m/s	102.9 ± 44.3 ++	101.4 ± 41.4 ++	80.1 ± 26.8

** significantly ($p<0.01$) greater than neutral and flexion.

++ significantly ($p<0.01$) greater than flexion.

Frequency 1595 Hz

Postural dway parameter	Velocity of head movement	Horizontal head movement		
		Extension	**Neutral**	**Flexion**
TL (mm)	0.2 m/s	236.6 ± 139.9 ++	220.6 ± 150.7	207.9 ± 120.2
	1.0 m/s	238.5 ± 120.1	230.1 ± 138.1	215.1 ± 104.8
TLx (mm)	0.2 m/s	137.5 ± 77.5 +	134.7 ± 94.3	121.7 ± 63.1
	1.0 m/s	144.0 ± 67.1	141.1 ± 80.9	128.3 ± 59.4
TLy (mm)	0.2 m/s	147.2 ± 100.4 ++	129.8 ± 97.4	127.7 ± 88.8
	1.0 m/s	144.6 ± 90.6	136.0 ± 96.8	129.2 ± 76.0

+ $p<0.05$, ++ $p<0.01$ significantly greater than flexion.

Frequency 2916 Hz

Postural sway parameter	Velocity of head movement	Horizontal head movement		
		Extension	**Neutral**	**Flexion**
TL (mm)	0.2 m/s	211.7 ± 112.9 +	197.4 ± 121.1	196.1 ± 97.1
	1.0 m/s	254.8 ± 132.0 **	197.4 ± 91.7	207.9 ± 101.9
TLx (mm)	0.2 m/s	123.3 ± 63.3	116.0 ± 68.7	114.5 ± 52.4
	1.0 m/s	153.6 ± 79.7 **	118.4 ± 51.1	118.6 ± 54.0
TLy (mm)	0.2 m/s	131.6 ± 85.2 *	120.1 ± 84.5	119.1 ± 73.5
	1.0 m/s	155.4 ± 93.7 **	116.9 ± 67.4 +	130.1 ± 78.8

* $p<0.05$, ** $p<0.01$ significantly greater than neutral and flexion.

+ significantly ($p<0.05$) greater or less than flexion.

Table 11.19 The interaction between sound, velocity and horizontal head movement with the neck extended, in neutral and flexed on the total path length (TL) and path length in the mediolateral (TLx) and anteroposterior (TLy) directions (mean ± SD).

No sound

Postural sway parameter	Velocity of head movement	Vertical head movement		
		Left	Looking ahead	Right
TL (mm)	0.2 m/s	126.2 ± 42.5	120.0 ± 28.1	128.1 ± 40.8
	1.0 m/s	154.9 ± 43.4	161.2 ± 55.2	160.3 ± 48.2
TLx (mm)	0.2 m/s	82.3 ± 30.9	75.7 ± 22.7	81.9 ± 28.5
	1.0 m/s	96.9 ± 33.1	94.6 ± 39.3	103.9 ± 36.5
TLy (mm)	0.2 m/s	76.6 ± 25.0	74.8 ± 14.7	78.8 ± 25.1
	1.0 m/s	98.4 ± 24.8	108.0 ± 35.1	98.0 ± 27.0

Frequency 1595 Hz

Postural sway parameter	Velocity of head movement	Vertical head movement		
		Left	Looking ahead	Right
TL (mm)	0.2 m/s	222.8 ± 100.7	213.9 ± 119.9	211.5 ± 102.0
	1.0 m/s	238.0 ± 106.0 *	253.0 ± 109.6	247.5 ± 103.7
TLx (mm)	0.2 m/s	134.4 ± 59.2	115.8 ± 64.4	122.4 ± 60.4
	1.0 m/s	136.5 ± 57.6	129.6 ± 61.7	141.6 ± 57.8
TLy (mm)	0.2 m/s	134.8 ± 70.1	139.7 ± 88.9	131.5 ± 74.0
	1.0 m/s	150.9 ± 78.9 **	176.7 ± 81.1	158.9 ± 76.6 *

* $p<0.05$, ** $p<0.01$ significantly less than looking direction ahead.

Frequency 2916 Hz

Postural sway parameter	Velocity of head movement	Vertical head movement		
		Left	Looking ahead	Right
TL (mm)	0.2 m/s	203.3 ± 106.1 **	207.5 ± 108.1 *	225.6 ± 121.3
	1.0 m/s	245.9 ± 112.2	249.3 ± 107.7	247.6 ± 105.3
TLx (mm)	0.2 m/s	117.6 ± 57.6 *	116.4 ± 54.8 *	131.0 ± 68.4
	1.0 m/s	142.2 ± 64.4	132.4 ± 67.2	142.0 ± 62.7
TLy (mm)	0.2 m/s	125.6 ± 77.0 *	131.1 ± 82.7	140.6 ± 86.0
	1.0 m/s	156.3 ± 83.2	169.1 ± 73.1	157.7 ± 73.5

* $p<0.05$, ** $p<0.01$ significantly less than rotation to the right.

Table 11.20 The interaction between sound, velocity and vertical head movement with looking directly ahead, rotation to the right or left on the total path length (TL) and path length in the mediolateral (TLx) and anteroposterior (TLy) directions (mean ± SD).

For diagonal head movement no significant differences in TL, TLx and TLy were observed for any combination of neck position, velocity and sound condition (Table 11.21). However, without sound at the lower velocity there was a significant ($p<0.01$) reduction in TL, TLx and TLy with both diagonal head movements compared with horizontal head movement with neck extension. In addition, a significant decrease in TL ($p<0.01$), TLx and TLy ($p<0.01$) was observed for LE diagonal head movement compared with vertical head movement with rotation to the left. Without sound at the higher velocity there was a significant increase in TL, due to the significant ($p<0.01$) increase in TLy, with RE diagonal head movement compared with horizontal head movement with neck flexion. A significant ($p<0.01$) decrease in TLy was also observed with LE diagonal head movement compared with vertical head movement with rotation to the right and left.

No sound

Postural sway parameter	Velocity of head movement	Diagonal head movement	
		LE	RE
TL (mm)	0.2 m/s	116.1 ± 39.7	117.3 ± 46.0
	1.0 m/s	145.0 ± 44.8	149.4 ± 36.6
TLx (mm)	0.2 m/s	75.0 ± 27.5	74.4 ± 32.9
	1.0 m/s	95.5 ± 34.9	94.8 ± 28.9
TLy (mm)	0.2 m/s	70.9 ± 24.2	72.8 ± 28.0
	1.0 m/s	86.6 ± 23.4	93.5 ± 20.9

Frequency 1595 Hz

Postural sway parameter	Velocity of head movement	Diagonal head movement	
		LE	RE
TL (mm)	0.2 m/s	238.5 ± 123.3	216.8 ± 94.9
	1.0 m/s	265.3 ± 118.3	240.8 ± 102.5
TLx (mm)	0.2 m/s	138.9 ± 78.0	128.0 ± 53.8
	1.0 m/s	153.1 ± 64.0	140.8 ± 59.5
TLy (mm)	0.2 m/s	148.4 ± 80.1	132.4 ± 71.8
	1.0 m/s	169.5 ± 87.4	149.8 ± 75.9

Frequency 2916 Hz

Postural sway parameter	Velocity of head movement	Diagonal head movement	
		LE	RE
TL (mm)	0.2 m/s	243.6 ± 141.0	212.1 ± 95.6
	1.0 m/s	255.1 ± 109.4	238.9 ± 112.5
TLx (mm)	0.2 m/s	142.6 ± 81.3	121.4 ± 55.9
	1.0 m/s	145.8 ± 62.4	135.5 ± 63.7
TLy (mm)	0.2 m/s	151.5 ± 98.8	133.7 ± 72.3
	1.0 m/s	163.4 ± 85.0	153.8 ± 85.2

Table 11.21 The interaction between sound, velocity and diagonal head movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the total path length (TL) and path length in the mediolateral (TLx) and anteroposterior (TLy) directions (mean ± SD).

No differences were observed between diagonal and horizontal or vertical head movement at 1595Hz with the lower velocity, however at the higher velocity there was a significant increase in TL, due to the significant ($p<0.01$) increase in TLy, with RE diagonal head movement and a significant ($p<0.01$) increase in TL, due to the increase in TLx and TLy ($p<0.01$) with LE diagonal head movement compared with horizontal head movement with neck flexion. No differences were observed for diagonal head movement compared with vertical head movement at 1595Hz at the higher velocity.

At 2916Hz and the lower velocity of movement there was a significant increase in TL, due to the significant ($p<0.01$) increase in Tly, for RE diagonal head movement and a significant ($p<0.01$) increase in TL, due to the significant ($p<0.01$) increase in TLx and TLy, for LE diagonal head movement compared to horizontal head movement with neck flexion. In addition, there was a significant ($p<0.01$) increase in TL, TLx and TLy with LE diagonal head movement compared to vertical head movement with rotation to the left. At 2916Hz at the higher velocity there was a significant ($p<0.01$) increase in TL, due to increase in TLx and TLy ($p<0.01$) with both diagonal head movements compared with horizontal head movement with neck flexion. No differences were observed in TL, TLx and TLy with diagonal compared with vertical head movement at 2916Hz at the higher velocity.

As shown in Table 11.22-11.24 the differences observed for the mean velocity of sway and the velocity of sway in the mediolateral and anteroposterior directions were similar to those reported for path length.

No sound

Postural sway parameter	Velocity of head movement	Horizontal head movement		
		Extension	Neutral	Flexion
Vm (mm/s)	0.2 m/s	7.28 ± 2.67 **	6.11 ± 1.86	6.07 ± 1.94
	1.0 m/s	8.94 ± 4.17 ++	9.09 ± 4.10 ++	6.87 ± 2.22
Vxm (mm/s)	0.2 m/s	4.73 ± 1.76 **	3.95 ± 1.27	4.00 ± 1.40
	1.0 m/s	6.09 ± 3.25 ++	6.36 ± 3.11 ++	4.62 ± 1.59
Vym (mm/s)	0.2 m/s	4.45 ± 1.78 **	3.72 ± 1.21	3.61 ± 1.11
	1.0 m/s	5.16 ± 2.22 ++	5.09 ± 2.08 ++	4.02 ± 1.35

** significantly ($p<0.01$) greater than neck in neutral and neck flexed.
++ significantly ($p<0.01$) greater than neck flexed.

Frequency 1595 Hz

Postural sway parameter	Velocity of head movement	Horizontal head movement		
		Extension	Neutral	Flexion
Vm (mm/s)	0.2 m/s	11.9 ± 7.02 ++	11.1 ± 7.56	10.4 ± 6.03
	1.0 m/s	12.0 ± 6.03	11.5 ± 6.93	10.8 ± 5.26
Vxm (mm/s)	0.2 m/s	6.90 ± 3.89 +	6.76 ± 4.73	6.10 ± 3.17
	1.0 m/s	7.23 ± 3.37	7.08 ± 4.06	6.44 ± 2.98
Vym (mm/s)	0.2 m/s	7.39 ± 5.04 ++	6.51 ± 4.89	6.41 ± 4.46
	1.0 m/s	7.26 ± 4.55	6.82 ± 4.86	6.48 ± 3.81

+ $p<0.05$, ++ $p<0.01$ significantly greater than flexion.

Frequency 2916 Hz

Postural sway parameter	Velocity of head movement	Horizontal head movement		
		Extension	Neutral	Flexion
Vm (mm/s)	0.2 m/s	10.6 ± 5.66 +	9.90 ± 6.08	9.84 ± 4.87
	1.0 m/s	12.8 ± 6.62 **	9.91 ± 4.60	10.4 ± 5.11
Vxm (mm/s)	0.2 m/s	6.19 ± 3.18	5.82 ± 3.45	5.75 ± 2.63
	1.0 m/s	7.71 ± 4.00 **	5.94 ± 2.56	5.95 ± 2.71
Vym (mm/s)	0.2 m/s	6.60 ± 4.27 *	6.03 ± 4.24	5.97 ± 3.69
	1.0 m/s	7.80 ± 4.70 **	5.87 ± 3.38 +	6.53 ± 3.96

* $p<0.05$, ** $p<0.01$ significantly greater than neutral and flexion.
+ significantly ($p<0.05$) greater or less than flexion.

Table 11.22 The interaction between sound, velocity and horizontal head movement with the neck extended, in neutral and flexed on the mean velocity of sway (Vm) and velocity of sway in the mediolateral (Vxm) and anteroposterior (Vym) directions (mean ± SD).

No sound

Postural sway parameter	Velocity of head movement	Vertical head movement		
		Left	Looking ahead	Right
Vm (mm/s)	0.2 m/s	6.33 ± 2.13	6.02 ± 1.41	6.43 ± 2.05
	1.0 m/s	7.77 ± 2.18	8.09 ± 2.77	8.04 ± 2.42
Vxm (mm/s)	0.2 m/s	4.13 ± 1.55	3.80 ± 1.14	4.11 ± 1.43
	1.0 m/s	4.86 ± 1.66	4.75 ± 1.97	5.21 ± 1.83
Vym (mm/s)	0.2 m/s	3.84 ± 1.25	3.75 ± 0.74	3.96 ± 1.26
	1.0 m/s	4.94 ± 1.24	5.42 ± 1.76	4.92 ± 1.35

Frequency 1595 Hz

Postural sway parameter	Velocity of head movement	Vertical head movement		
		Left	Looking ahead	Right
Vm (mm/s)	0.2 m/s	11.2 ± 5.05	10.7 ± 6.02	10.6 ± 5.12
	1.0 m/s	11.9 ± 5.32 *	12.7 ± 5.50	12.4 ± 5.20
Vxm (mm/s)	0.2 m/s	6.75 ± 2.97	5.81 ± 3.23	6.14 ± 3.03
	1.0 m/s	6.85 ± 2.89	6.50 ± 3.09	7.11 ± 2.90
Vym (mm/s)	0.2 m/s	6.76 ± 3.52	7.01 ± 4.46	6.60 ± 3.71
	1.0 m/s	7.57 ± 3.96 **	8.87 ± 4.07	7.97 ± 3.85 *

* $p<0.05$, ** $p<0.01$ significantly less than looking directly ahead.

Frequency 2916 Hz

Postural sway parameter	Velocity of head movement	Vertical head movement		
		Left	Looking ahead	Right
Vm (mm/s)	0.2 m/s	10.2 ± 5.32 **	10.4 ± 5.42 *	11.3 ± 6.09
	1.0 m/s	12.3 ± 5.63	12.5 ± 5.40	12.4 ± 5.28
Vxm (mm/s)	0.2 m/s	5.90 ± 2.89 *	5.84 ± 2.75 *	6.57 ± 3.43
	1.0 m/s	7.14 ± 3.23	6.64 ± 3.37	7.12 ± 3.15
Vym (mm/s)	0.2 m/s	6.30 ± 3.86 *	6.58 ± 4.15	7.06 ± 4.32
	1.0 m/s	7.84 ± 4.17	8.49 ± 3.67	7.91 ± 3.69

* $p<0.05$, ** $p<0.01$ significantly less than rotation to the right.

Table 11.23 The interaction between sound, velocity and vertical head movement with looking directly ahead, rotation to the right or left on the mean velocity of sway (Vm) and velocity of sway in the mediolateral (Vxm) and anteroposterior (Vym) directions (mean ± SD).

No sound

Postural sway parameter	Velocity of head movement	Diagonal head movement	
		LE	RE
Vm (mm/s)	0.2 m/s	5.83 ± 1.99	5.88 ± 2.31
	1.0 m/s	7.28 ± 2.25	7.50 ± 1.84
Vxm (mm/s)	0.2 m/s	3.76 ± 1.38	3.73 ± 1.65
	1.0 m/s	4.79 ± 1.75	4.76 ± 1.45
Vym (mm/s)	0.2 m/s	3.56 ± 1.22	3.65 ± 1.40
	1.0 m/s	4.34 ± 1.17	4.69 ± 1.05

Frequency 1595 Hz

Postural sway parameter	Velocity of head movement	Diagonal head movement	
		LE	RE
Vm (mm/s)	0.2 m/s	12.0 ± 6.19	10.9 ± 4.76
	1.0 m/s	13.3 ± 5.94	12.1 ± 5.14
Vxm (mm/s)	0.2 m/s	6.97 ± 3.92	6.43 ± 2.70
	1.0 m/s	7.68 ± 3.21	7.06 ± 2.99
Vym (mm/s)	0.2 m/s	7.45 ± 4.02	6.64 ± 3.60
	1.0 m/s	8.51 ± 4.38	7.52 ± 3.81

Frequency 2916 Hz

Postural sway parameter	Velocity of head movement	Diagonal head movement	
		LE	RE
Vm (mm/s)	0.2 m/s	12.2 ± 7.07	10.6 ± 4.80
	1.0 m/s	12.8 ± 5.49	12.0 ± 5.65
Vxm (mm/s)	0.2 m/s	7.15 ± 4.08	6.09 ± 2.81
	1.0 m/s	7.32 ± 3.13	6.80 ± 3.20
Vym (mm/s)	0.2 m/s	7.60 ± 4.96	6.71 ± 3.63
	1.0 m/s	8.20 ± 4.27	7.72 ± 4.27

Table 11.24 The interaction between sound, velocity and diagonal head movement with the neck rotated to the left and extended (LE) and rotated to the right and extended (RE) on the mean velocity of sway (Vm) and velocity of sway in the mediolateral (Vxm) and anteroposterior (Vym) directions (mean ± SD).

11.4 Discussion

As reported for Experiments 2 (Chapter 5) and 4 (Chapter 8) there was no difference in age between the female and male groups. However, height, foot length and eye level height were significantly greater while eye-object distance was significant smaller, in the males than in the females.

The influence of gender can be observed on the position of the COG projection in the mediolateral direction, being more to the right in females. This is probably due to vision being a more potent input in males (Kollegger et al. 1992).

The presence of sound generally increases postural sway behaviour (Juntunen et al. 1987; Raper and Soames 1991; Kilburn et al. 1992; Soames and Raper 1992; Sakellari and Soames 1996). However, the findings in this experiment do not support this observation since a decrease in the mediolateral and anteroposterior sway magnitudes and an increase in path lengths and velocities was observed. Somewhat surprisingly, the previous reported stabilising effect of 1595Hz was observed to cause greater postural sway in the mediolateral direction than the destabilising effect 2916Hz. This finding is opposite to that observed in Chapter 10 and the observations reported by Sakellari and Soames (1996). One possible explanation of this difference is that the head was moving in the present study but static in the Chapter 10, as well as in the experiment of Sakellari and Soames (1996). It is suggested that in the presence of an auditory input movement of the head reduces both the mediolateral and anteroposterior sway magnitude, as well as postural sway behaviour in the mediolateral direction induced by the destabilising effect of sound.

The velocity of head movement was observed to influence postural sway behaviour in both the mediolateral and anteroposterior directions, as well as the angle of sway from the sagittal plane. This is due to the higher velocity of movement stimulation of the vestibular system (Livingston 1990). Galvanic vestibular stimulation leads to an increase in lateral (Johansson and Magnusson

1991) and anteroposterior (Magnusson et al. 1991; Fitzpatrick et al. 1994a; Inglis et al. 1995) sway, but does not change the mean angle of sway (Mihalik 1992). It is, therefore suggested that vestibular stimulation leads to postural destabilisation. However, the vestibular stimulation induced by head movement leads to a reduction in the angle of sway from the sagittal plane.

Horizontal head movement with the neck flexed/extended or neutral reveals that extension induces greater postural instability than does flexion or the neutral position. This may be due to differences in the activation of hair cells in the vestibular system. Neck extension causes hair cells depolarisation, while neck flexion leads to their hyperpolarisation (Livingston 1990; Sherwood 1997). It is suggested the depolarisation of the hair cells of the vestibular system leads to postural destabilisation.

Vertical head movement with rotation to the right or left exhibits increased mediolateral postural instability, but increased stability anteroposteriorly. Unilateral neck stimulation has been shown to induce lateral sway (Smetanin et al. 1993). It is, therefore suggested that asymmetrical neck proprioception causes postural instability in the mediolateral direction, but leads to postural stability in the anteroposterior direction by having an effect similar to unilateral muscle stimulation.

Comparison between head movement in the various directions indicates that the interaction between vestibular and neck proprioceptor inputs leads to a decrease in sway behaviour compared with vestibular input in neck extension, but increases sway behaviour compared with vestibular input in neck flexion. In addition, this interaction also increases the total path length and mean velocity of sway, as well as that in the mediolateral and anteroposterior directions separately, compared with neck proprioceptor input. It is, therefore suggested that the interaction between vestibular and neck proprioceptor inputs is additive, as observed by Karnath et al. (1994), but that it is dependent on the vestibular input. The reason being that in the mediolateral direction diagonal head movement causes a decrease in mediolateral sway compared with horizontal head movement with neck extension. Neck extension and neck rotation are responsible for the increase in mediolateral sway, but neck flexion decreases it. The decrease in mediolateral sway associated with diagonal head movement is possibly due to the effect of neck flexion. In the anteroposterior direction diagonal head movement causes an increase in sway compared with horizontal head movement with neck flexion. In addition, in the anteroposterior direction neck extension also leads to an increase in sway, but neck flexion and neck rotation produces a decrease. The increase in anteroposterior sway for diagonal head movement is possibly due to the effect of neck extension. The increase in path lengths and velocities of sway associated with diagonal head movement compared with vertical head movement may also be due to the influence of neck extension.

The interaction between sound and the direction of head movement shows that it is the vestibular inputs from neck extension which leads to postural instability. This interaction seems to depend on the vestibular input since sway behaviour is increased or decreased with neck flexion/extension for all sound conditions. The interaction between sound and neck proprioception destabilises posture in the mediolateral direction, but stabilises it in the anteroposterior direction. Sound at 1595Hz tends to increase mediolateral, but not anteroposterior, sway. It is, therefore suggested that the interaction between sound and neck proprioception depends on the nature of the auditory input. The interaction between auditory, vestibular and neck proprioceptor input shows a greater or less sway behaviour than the interaction between the auditory and vestibular systems. It is suggested that neck proprioceptor input is an important cue in the combination of auditory, vestibular and neck proprioceptor inputs leading to postural stability or instability.

The velocity and direction of head movement interaction influences sway behaviour in the anteroposterior direction. For horizontal head movement the findings show that the interaction between input from the otoliths during neck extension and the semicircular canals leads to an increase in sway magnitude. It is suggested that such interaction depends on the otolith organs. In addition, the vestibular system depends on the velocity of head movement. For vertical head movement it has been shown that it is the influence of the vestibular system on neck proprioceptor input that leads to an increase in postural stability. For diagonal head movement at both velocities of movement sway behaviour is increased compared with neck flexion, at the lower velocity it also is increased compared with neck rotation. The vestibular system appears to be an important cue in the vestibular-neck proprioceptor interaction in postural maintenance.

The interaction between sound, velocity and the direction of head movement reveals that for horizontal head movements the interaction between auditory and vestibular input with neck extension increases postural sway behaviour in the mediolateral direction. In the anteroposterior direction this interaction also shows postural destabilisation. The interaction is more clearly observed at 1595Hz at the lower velocity, but is also seen at 2916Hz at the higher velocity. It is proposed that the auditory input is selected to interact with the vestibular under specific conditions. For vertical head movement at the lower velocity the interaction between auditory and neck proprioceptor input increases mediolateral sway magnitude. This may be due to the effect of the auditory input in the mediolateral direction (Sakellari and Soames 1996), as well as aysmmetric neck proprioception. The interaction between sound and neck proprioceptor is present at 1595Hz but not 2916Hz. It is suggested that the auditory input is selected to interact with neck proprioception influencing posture in the mediolateral direction. For vertical head movement at the higher velocity there is a clear interaction between the auditory, vestibular and neck proprioceptor systems. Such interaction acts to stabilise the anteroposterior path length and sway. It is further suggested that dynamic vestibular stimulation is an important factor in such an interaction in the control of posture in the anteroposterior direction. For diagonal head movement the auditory-vestibular-neck proprioceptor interaction stabilises mediolateral sway, but destabilises path length and velocity of sway. It is, therefore suggested that vestibular input reduces the mismatch between sound and neck proprioception in controlling mediolateral sway and position, with the vestibular system controlling path length and sway velocity.

11.5 Summary

Auditory, vestibular and neck proprioceptor inputs all influence the precision of postural control. During dynamic head movements the presence of an auditory input acts to stabilise posture, while the vestibular input destabilises it. There appears to be an interaction between auditory and vestibular inputs associated with neck extension resulting in increased postural instability which depends on vestibular cues. The auditory-neck proprioceptor interaction stabilises posture in the anteroposterior direction but destabilises it in the mediolateral direction. In the vestibular-auditory and neck proprioceptor-auditory interactions the auditory input appears to be selected to interact with the vestibular or neck proprioceptor system under specific conditions. The vestibular-neck proprioceptor interaction leads to postural stability and is dependent on the vestibular input. The interaction between the auditory, vestibular and neck proprioceptor systems acts to decrease mediolateral sway, but increase path lengths and sway velocity. In such interactions the vestibular system is an important cue leading to stabilisation or destabilisation of posture.

Chapter 12
Discussion and conclusions

12.1 Discussion

The individual and interactive effects of visual, vestibular, neck proprioceptor and auditory input are important in the maintenance of upright posture. In addition, gender also influences postural sway behaviour and postural control.

The sex differences in postural maintenance observed in this study show that females exhibit a greater mediolateral COG projection, total path length and mean velocity of sway, as well as the path length and the velocity of sway in the mediolateral direction than males. The suggestion, therefore is that females are less stable in the mediolateral direction than males. In contrast, females are more stable in the anteroposterior direction than males as seen in the forward COG projection and decrease in the angle of sway from the sagittal plane. The interaction between sex and the various sensory systems reveals that visual feedback and static neck proprioceptor input are stabilising factors in males, whereas auditory, vestibular and neck proprioceptor inputs appear to be stabilising factors in females. In males, the visual system is dominant in stabilising mediolateral sway behaviour whereas static neck proprioceptor input is dominant in stabilising anteroposterior sway behaviour. In contrast, in females the auditory system is important for stabilising sway in the mediolateral direction, whereas dynamic vestibular and neck proprioceptor inputs as well as the interaction between static vestibular and neck proprioceptor appear to stabilise sway in the anteroposterior direction. This suggests that of the four sensory modalities studied the visual and auditory systems are important in the mediolateral postural control, whereas vestibular and neck proprioceptor are dominant in the anteroposterior postural organisation in humans. The findings with respect to visual feedback in this study agrees with the importance of the visual system in males reported by Kollegger et al. (1992), particularly the role of visual input in controlling mediolateral sway (Day et al. 1993).

As with previous studies (Kollegger et al. 1989, 1992; Toupet et al. 1992; Colledge et al. 1994) the loss of visual feedback was observed to lead to postural instability. In all conditions without visual feedback the postural destabilisation is seen as a shift in the mediolateral and anteroposterior COG projections, an increase in sway magnitude in both the mediolateral and anteroposterior directions, as well as total path length and mean velocity of sway, including the path length and velocities in the mediolateral and anteroposterior direction separately. Thus, in addition to perceiving the position of the head in space (Guitton et al. 1986; Pozzo et al. 1990; Kanaya et al. 1995), the visual system also provides information about the body in space. However, the visual system does not control the direction of body movements during postural maintenance. For controlling the mediolateral and anteroposterior COG projection the function of the visual system appears to depend on the prevailing environmental conditions.

Neck flexion and extension both change the position of head resulting in a change in the activation pattern of the otolith organs (Livingston 1990; Sherwood 1997), with extension having a more powerful effect than flexion on postural maintenance under conditions of both static and dynamic stimulation. This can be explained by activation of the hair cells in the vestibular system. In extension the stereocilia are bent toward the kinocilium causing depolarisation of the hair cells, whereas in flexion the stereocilia are bent away from the kinocilium causing hyperpolarisation of the hair cells (Livingston 1990; Sherwood 1997). Thus, stimulation of the vestibular system by neck extension leads to decreased postural stability compared with neutral or flexion. Static and dynamic stimulation of the vestibular system do not appear to have a different effect on postural control. However, static vestibular stimulation leads to a greater increase in postural stability than does dynamic stimulation. The vestibular system influences both mediolateral and anteroposterior sway magnitude, as well as total path length and mean velocity of sway. In addition, it appears to control the COG projection anteroposteriorly but not mediolaterally. There also appears to be an influence of the vestibular system on the angle of sway from the sagittal plane, however this is dependent on the prevailing environmental conditions.

Neck rotation clearly changes the nature of the neck proprioceptor input. Stimulation of the neck muscles has been reported to cause postural destabilisation (Lund 1980; Smetanin et al. 1993). The findings of the present study indicate that in some conditions neck proprioceptor stimulation leads to postural stabilisation. Static neck proprioceptor stimulation resulted in postural destabilisation seen as an increase in mean mediolateral sway magnitude, path length and sway velocity, with changes in the mediolateral path length and sway velocity leading to the change in the mediolateral COG projection. Static neck proprioceptor stimulation also decreased anteroposterior postural stability observed as an increase in anteroposterior sway magnitude, a posterior shift of the anteroposterior COG projection and a reduced angle of sway from the sagittal plane. The neck proprioceptor system is, therefore important in controlling the deviations of the body: this finding agrees with the observations of Smetanin et al. (1993). Dynamic neck proprioceptor stimulation had a similar influence as did static neck proprioceptor stimulation for the mediolateral direction, except there was no change in the mediolateral COG projection. In contrast, dynamic neck proprioceptor stimulation resulted in increased postural stabilisation in the anteroposterior direction by reducing sway magnitude, particularly posteriorly, path length and sway velocity. Thus, it is suggested that neck proprioceptor input causes postural destabilisation in the mediolateral direction. In addition, static neck proprioceptor input leads to postural instability in the anteroposterior direction, while dynamic stimulation leads to postural stability.

Sound appears to be an important factor influencing postural maintenance. The findings in this study agree with the observation of several researchers (Juntunen et al. 1987; Raper and Soames 1991; Kilburn et al. 1992; Soames and Raper 1992; Sakellari and Soames 1996). Under conditions of static vestibular and neck proprioceptor stimulation sound decreases postural stability by increasing sway magnitude in both the mediolateral and anteroposterior directions, as well as total path length and mean velocity of sway, including those separately in the mediolateral and anteroposterior directions. In addition, sound also appears to decrease body deviations from the sagittal plane. Comparison of the two frequencies used showed that 2916Hz had a more destabilising effect than did 1595Hz, thus confirming the finding of Sakellari and Soames (1996). This observation was seen as an increase in mediolateral sway magnitude. It is suggested that auditory input at different frequencies influence mediolateral sway magnitude. For dynamic vestibular and neck proprioceptor stimulation sound decreases sway magnitude in both the mediolateral and anteroposterior directions, but increases the total path length and mean velocity, including the mediolateral and anteroposterior directions separately, as well as the angle of sway. Of the two frequencies of sound used the influence on stability in the mediolateral direction with 2916Hz was greater than that of 1595Hz. The influence of these two frequencies on postural stability in static and dynamic stimulation conditions is therefore reversed. It is suggested that head movement stimulating the vestibular and neck proprioceptors reduces the postural instability induced by the destabilising effect of sound. Thus, it is suggested that auditory feedback reduces postural stability particularly in the mediolateral direction, while movement of the head can counteract the destabilising effect of sound.

The interaction between visual and vestibular inputs influences most postural sway parameters. The destabilising effect of neck extension on sway behaviour is reduced with visual feedback. In contrast, with visual feedback and neck flexion there is an increase in both mediolateral and anteroposterior sway magnitude compared the neutral neck position. It is, therefore suggested that vision counteracts the vestibular input associated with neck extension, but accentuates it with neck flexion. It is possible that neck flexion causes hyperpolarisation of the vestibular system (Livingston 1990; Sherwood 1997), thereby disproportionately enhancing the importance of visual information in postural stabilisation. Thus, the interaction between vision and the vestibular system seems to depend on the extent of agreement between them, thereby confirming the findings of Zacharias and Young (1981).

The interaction between vision and neck proprioception also influences several postural sway parameters: the anteroposterior COG projection, the mediolateral and anteroposterior sway magnitude, total path length and mean velocity of sway, particularly in the mediolateral direction. This interaction works to decrease postural stability. Neck muscle stimulation is known to change the direction of eye movement (Han and Lennestrand 1995) and induce displacement of the visual target (Biguer et al. 1988). The decrease in postural stability observed may be due to the mismatch between vision and neck proprioceptor input influencing gaze stabilisation. However, neck proprioceptor input alone controls deviation of the body, while visual feedback provides information about body and head position in space (Paulus et al. 1984; Guitton et al. 1986; Pozzo et al. 1990; Kanaya et al. 1995). Consequently, the interactive effect reduces the angle of sway indicating that it has a role to play in the control of the direction of sway, confirming the observation of Wolsley et al. (1996). The interaction between vision and neck proprioception appears to be additive.

The interaction between the visual and auditory systems influenced some sway parameters but not others: the mediolateral COG projection and mean sway velocity, including both the mediolateral and anteroposterior directions separately. Lueck et al. (1990) showed that the horizontal saccades generated by the visual-auditory interaction depend on the visual stimulus. In addition, Sakellari and Soames (1996) showed the visual-auditory interaction on postural control that the auditory system is more dominant than the visual in postural maintenance in the mediolateral direction. The importance of the visual-auditory interaction cannot be determined from the studies conducted. Nevertheless, the findings provide possible evidence for a visual-auditory interaction in humans.

The interaction between vestibular and neck proprioception influences all sway parameters except the angle of sway. This interaction shows a difference between static and dynamic stimulation, with the positive influence being during dynamic stimulation. For static stimulation the interaction leads to anteroposterior postural instability without auditory input, but in contrast with auditory input the interaction destabilises posture in the mediolateral direction. For dynamic stimulation with and without auditory input the interaction appears to reduce anteroposterior sway magnitude, path length and sway velocity, perhaps leading to a decrease in total path length and mean sway velocity. It is suggested that dynamic stimulation of the vestibular and neck proprioceptors stabilises posture in the anteroposterior direction, with vestibular input assisting neck proprioceptor input in controlling posture.

The interaction between vestibular and auditory inputs differs depending on whether there is static or dynamic vestibular stimulation. For static stimulation the interaction influences only the mean anteroposterior COG position shifting it anteriorly. The results from the present studies suggest that the vestibular-auditory interaction stabilises posture in the anteroposterior direction, with sound having a greater influence with neck extension than neck flexion, since extension causes depolarisation of the vestibular system. The interaction with static stimulation depends on the auditory input, since with sound the COG projection shifts anteriorly. With dynamic stimulation it causes postural destabilisation by shifting the COG projection posteriorly, as well as increasing both mediolateral and anteroposterior sway magnitude, total path length and mean velocity of sway, including both the mediolateral and anteroposterior directions separately. The effect of the interaction is most strongly seen in the mediolateral direction. With dynamic stimulation the interaction appears to depend on the vestibular input, since there is no difference in sway behaviour either with or without sound, but there is a difference between neck extension and flexion. From these findings it is suggested that both components of the vestibular-auditory interaction are important causing either postural stability or instability depending on the nature of the stimulation.

The interaction between neck proprioceptor and auditory input influence the anteroposterior COG projection and sway magnitude, as well as path length and sway velocity in both the mediolateral and anteroposterior directions. Even though there is a change in path length and sway velocity in both the mediolateral and anteroposterior directions, the total path length and mean velocity of sway are not affected. This is because there is an increase in the mediolateral, but a decrease in the anteroposterior direction. In conditions of both static and dynamic stimulation the effect appears to be to destabilise posture mediolaterally, but stabilise it anteroposteriorly. This difference may be due to the individual effect of neck rotation and sound, each tending to increase postural sway behaviour in the mediolateral direction. In addition, neck proprioception, particularly with dynamic stimulation, reduces anteroposterior sway while sound does not appear to have a strong influence in this direction. This implies that the effects are additive. In this study the interaction between neck proprioceptor and auditory inputs shows a difference with neck rotation to the right and left under some experimental conditions. This finding may be linked with handedness, although there is no evidence to suggest that this is the case.

The visual, vestibular and neck proprioceptor interaction influences the magnitude of posterior sway, total path length, anteroposterior path length as well as mean velocity of sway, suggesting that the interaction is important in the control of posture in the anteroposterior direction. It was observed that vision was generally a stabilising factor in managing the mismatch between vestibular and neck proprioceptor inputs. However, this interaction increases the magnitude of sway posteriorly. This may be due to an inappropriate vestibular input associated with neck flexion. In the present study the effect of the visual-vestibular-neck proprioceptor interaction was not observed with sound, suggesting that the interaction is not modified by auditory input.

The interaction between the visual, vestibular and auditory systems only influenced the magnitude of sway to the left, implying that it regulates postural control in the mediolateral direction. The vision-vestibular-auditory interaction occurs when auditory input destabilises posture, with input from the visual system appearing to be the stabilising factor. However, input from the vestibular system induced by neck flexion appears to create a conflict with visual input causing an increase in sway to the left.

The interaction between vision, neck proprioceptor and auditory input influences the anteroposterior COG projection as well as the magnitude of posterior sway, suggesting that this interaction is important in controlling posture in the anteroposterior direction. The interaction appears to stabilise the magnitude of posterior sway by causing a shift in the anteroposterior COG projection. There is a differential effect depending on the frequency of the sound: the implication is that the interaction is stabilising when the auditory input has a destabilising effect on posture. In this interaction it is expected that the neck proprioceptor input reduces the conflict between the visual and auditory inputs. The destabilising effect of the visual-neck proprioceptor-auditory interaction may be due to a mismatch between visual and neck proprioceptor input, with the auditory input appearing to minimise the conflict.

The vestibular, neck proprioceptor and auditory interaction has different effects depending on whether stimulation is static or dynamic. For static stimulation the interaction influences the anteroposterior COG projection and the angle of sway from the sagittal plane leading to increased postural stability: the interaction depending on the auditory input since at 1595Hz the effect is more stabilising. For dynamic stimulation the interaction influences the magnitude of sway in both the mediolateral and anteroposterior directions, total path length and mean velocity of sway, including both the mediolateral and anteroposterior directions separately. With dynamic stimulation the interaction does not to appear to depend on the auditory input, since there is similar pattern at both frequencies. The vestibular and neck proprioceptor input appears to be the stipulating cue leading to postural stabilisation or destabilisation.

The interaction between visual, vestibular, neck proprioceptor and auditory inputs is limited to the angle of sway from the sagittal plane. Such interaction controls posture by keeping the body from deviating from the sagittal plane.

The individual and interactive effect of vision, vestibular, neck proprioceptor and auditory inputs on postural sway behaviour are summarised in Table 12.1. The creation of postural instability may be the result of inappropriate individual sensory inputs or the conflict between different sensory cues. In humans sensory information enters the central nervous system (CNS) and modulates muscle activities resulting in a correction of posture (Johansson and Magnusson 1991). Since electrode implantation cannot be done in humans as it can in animals (Deliagina et al. 2000) there is, therefore no physiological evidence for defining the CNS pathways implicated in postural control. Nevertheless, from the individual and interactive effect of visual, vestibular, neck proprioceptor and auditory input

Sensory input	COG projection		Magnitude of sway		Path length			Velocity of sway			Angle of sway from the sagittal plane
	M-L	A-P	M-L	A-P	Total	M-L	A-P	Mean	M-L	A-P	
Individual											
Visual	*	*	*	*	*	*	*	*	*	*	
Vestibular		*	*	*	*	*	*	*	*	*	*
Neck	*	*	*	*		*	*		*	*	*
Auditory	*	*	*	*	*	*	*	*	*	*	*
Interaction											
Visual+Vestibular		*	*	*	*	*	*	*	*	*	*
Visual+Neck		*	*	*	*	*		*	*		*
Visual+Auditory	*							*	*	*	
Vestibular+Neck	*	*	*	*	*	*	*	*	*	*	
Vestibular+Auditory		*	*	*	*	*	*	*	*	*	
Neck+Auditory		*	*	*		*	*		*	*	
Visual+Vestibular+Neck				*	*		*	*			
Visual+Vestibular+Auditory			*								
Visual+Neck+Auditory		*		*							
Vestibular+Neck+Auditory		*	*	*	*	*	*	*	*	*	*
Visual+Vestibular+Neck+Auditory											*

Table 12.1 **The individual and interactive effects of vision, vestibular, neck proprioceptor (Neck) and auditory input on postural sway behaviour (COG = centre of gravity; M-L = mediolateral direction; A-P = anteroposterior direction).**

on postural sway behaviour it can be speculated and postulated that within the CNS there are area(s) and pathway(s) linking the individual and interactive information from the visual, vestibular, neck proprioceptor and auditory systems for the successful control of postural maintenance.

The individual effects of visual, vestibular, neck proprioceptor and auditory input implies that the visual, vestibular, neck proprioceptor and auditory systems have sensory-motor pathways involved in postural control. In addition, the interaction between visual, vestibular, neck proprioceptor and auditory input implies that in the CNS there are structure(s) and area(s) acting as integrative centres responsible for postural maintenance. The possible structures, areas and pathways in the CNS involved in postural control due to either the individual and interactive effects of visual, vestibular, neck proprioceptor and auditory inputs, are shown in Figure 12.1.

In addition to the visual pathway (Martin 1991; Pansky et al. 1992) it is suggested that efferent fibres from the superior colliculus travelling in the tectospinal (superior colliculus-spinal cord) and tectocerebellar tracts (superior colliculus-cerebellum) are possible pathways conveying visual information to the cervical spinal cord and cerebellum important in the control of posture. The superior colliculus also has efferent fibres projecting to the reticular formation (Pansky et al. 1992), however the function of the reticular formation with respect to vision is not well known. Nevertheless, the reticular formation has important functions for eye movement and motor control (Purves et al. 1997). It is, therefore possible that the pathway from the superior colliculus to the recticular formation is involved in postural maintenance. The superior colliculus is reported to be an integrating area for visual and auditory input (Lueck et al. 1990). In addition, the superior colliculus has efferent projections to the inferior colliculus (Pansky et al. 1992) and interchange visual and auditory information with the inferior colliculus (Livingston 1990). It is, therefore suggested that the inferior colliculus also acts to integrate visual and auditory input. The superior colliculus has pathways to the brainstem which probably serves in the reflex control and regulation of eye and head movement (Pansky et al. 1992). The vestibular nuclei have been reported to integrate vestibular and visual inputs (Henn et al. 1974), however in humans no

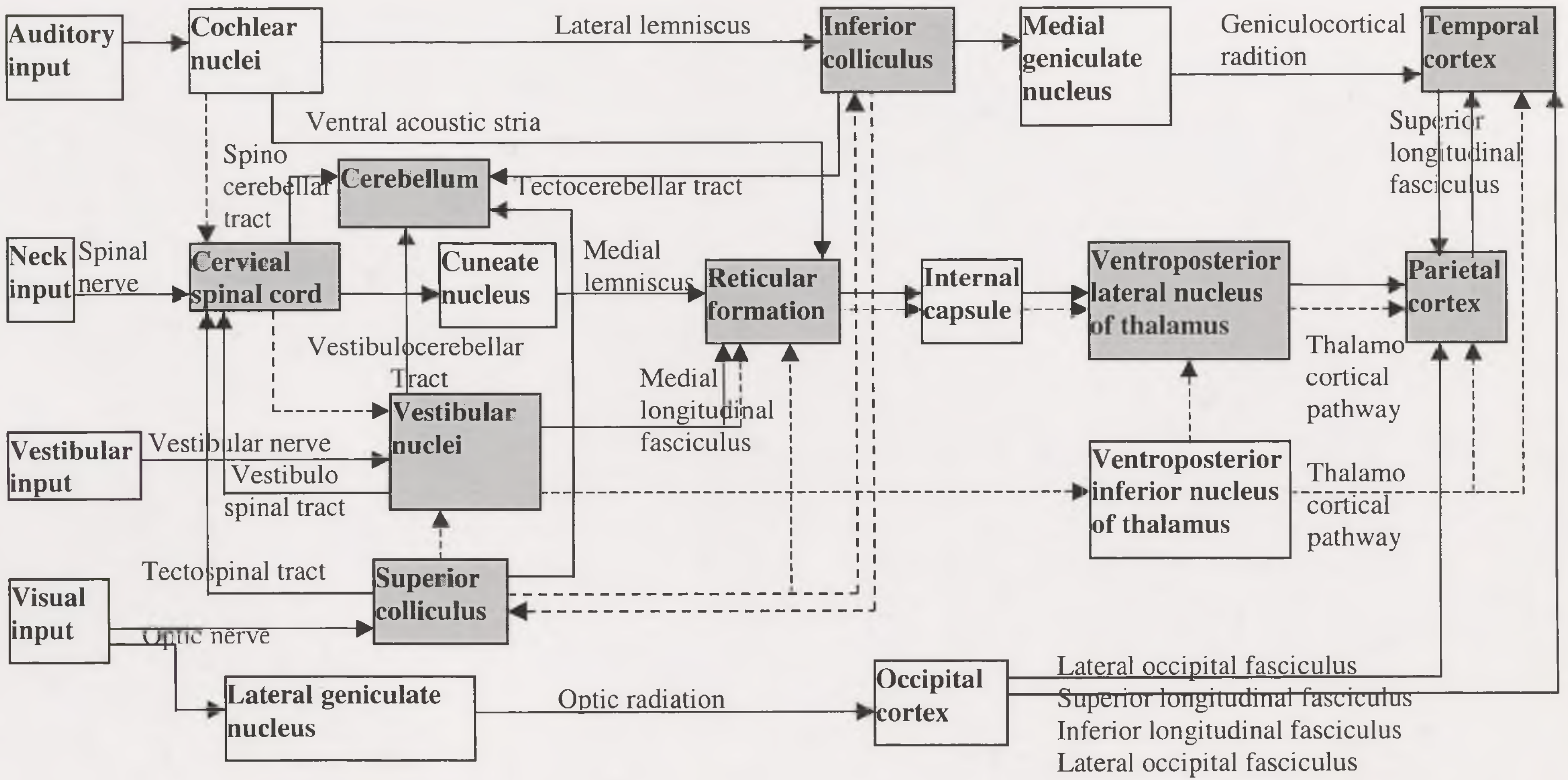


Figure 12.1 **Proposed areas and pathways within the central nervous system for both the individual and interactive sensory inputs influencing postural maintenance (grey box = integrating area, --- = speculative pathway).**

specific pathway has been reported to connect any structure in the visual pathway with the vestibular nuclei. Nevertheless, in the present study it is possible that visual input is transmitted from the superior colliculus to the vestibular nuclei for integration with vestibular input and then to the spinal cord for postural control, thus creating a visuo-motor pathway. Furthermore, in brainstem-lesioned cats it has been shown that neck proprioceptor inputs project to the vestibular nuclei to interact with vestibulo-ocular reflex activity (Hikosaka and Maeda 1983). Using a high-resolution positron emission tomography scanner it has been shown that when standing with feet together and eyes open there is activation of the associated areas of the visual cortex (Ouchi et al. 1999). Thus, visual input from the occipital cortex is transmitted to other area in the CNS. The possible areas to which the occipital cortex passes visual information are the parietal and temporal cortex via the lateral occipital fasciculus, superior and inferior longitudinal fasciculus. The parietal and temporal cortex acts as an integrating structure for visual input and other sensory modalities (Anderson et al. 1997; Duhamel et al. 1997; Elston et al. 1999).

The vestibular system appears to have a pathway from the vestibular nuclei to the cervical spinal cord, cerebellum and reticular formation via the vestibulospinal tract, vestibulocerebellar tract and medial longitudinal fasciculus, respectively (Martin 1991; Pansky et al. 1992; Shinoda et al. 1992). Practising standing with the head extended results in an improvement in postural balance, thus suggesting a vestibulospinal mechanism (Brandt et al. 1981). The cerebellum is associated with the vestibular system and plays a significant role in regulating muscle tone, equilibrium and posture (Pansky et al. 1992). The reticular formation is relevant with respect to nausea, vomiting and sweating following vestibular stimulation (Martin 1991). Furthermore, the reticular formation has been found to be an integration area for visual and vestibular interaction in the lamprey (Deliagina et al. 2000). The reticular formation receives input from the superior colliculus (Pansky et al. 1992), it is, therefore suggested that it is an integrative area for the interaction between vestibular and visual sensory inputs in humans. The reticular formation is also reported to be an integration area for the vestibular and neck proprioceptor systems (Siegel and Tomaszewski 1983). In addition to the cervical spinal cord, cerebellum and reticular formation, the temporoparietal cortex and the primary sensory cortex are also reported to receive vestibular input (Bottini et al. 1994).

In the rhesus monkey the ventroposterior inferior nucleus of the thalamus is closely related to the ventroposterior lateral nucleus of the thalamus and is the thalamic relay of the vestibulo-cortical pathway (Deecke et al. 1974). It is, therefore possible that the ventroposterior inferior nucleus has projections to the temporoparietal and primary sensory cortex, as well as to the ventroposterior lateral nucleus. The ventroposterior lateral nucleus may be an integrating area for vestibular-proprioceptor inputs to facilitate conscious perception of body position and movement in humans since it has certain direct pathways connecting to the primary sensory area in the parietal cortex (Pansky et al. 1992; Purves et al. 1997): many vestibular cells are found in the ventroposterior lateral nucleus of thalamus (Deecke et al. 1977). In addition, the pathway from the reticular formation to the parietal cortex for neck proprioceptor input may be another pathway for the vestibular input terminating in the primary sensory area in the parietal cortex.

The neck proprioceptor input is transmitted to the cervical spinal cord via spinal nerves and then to the cerebellum via the spinocerebellar tract (Martin 1991; Pansky et al. 1992). The vestibular nuclei are reported to be integrating structures for the vestibular and neck proprioceptor input in postural control of the head and trunk in the cat (Anatasopoulos and Mergner 1982). In the present study the interaction between vestibular and neck proprioceptor input has an influence on all postural sway behaviour parameters except the angle of sway. Thus, the vestibular nuclei are possibly an integrating area for the vestibular and neck proprioceptor input in postural control in humans. However, the pathway from the cervical spinal cord to the vestibular nuclei is not yet known. The neck proprioceptor input is transmitted to the reticular formation via the medial lemniscus then passes to the thalamus and terminates in the parietal cortex. The superior longitudinal fasciculus connects the parietal and temporal cortex, thus neck proprioceptor input may be relayed to the temporal cortex. The superior temporal polysensory area in the temporal cortex is reported to be an area for visual-neck proprioceptor integration (Elston et al. 1999).

The auditory system has been found to play role in postural maintenance. Although an audio-spinal pathway has not been established, auditory startle and auditory-spinal reflexes, originating from the brainstem, have been reported (Brown et al. 1991). The ventral acoustic stria connecting the cochlear nuclei and the reticular formation is one possible pathway to the brainstem involved in postural control. Furthermore, auditory input may project to the cerebellum via the tectocerebellar tract. The auditory input also terminates in the temporal cortex, which has also been found to integrate visual and auditory inputs (Elston et al. 1999). The auditory input to the temporal cortex may be transmitted to the parietal cortex to integrate with other sensory inputs to create abstract representation of space and used as a guide for movements (Anderson et al. 1997).

It is suggested that the cervical spinal cord, cerebellum, vestibular nuclei, reticular formation, superior and inferior colliculus, ventroposterior lateral nucleus of thalamus, temporal cortex and parietal cortex are all integration areas for sensory inputs controlling posture. Of these the spinal cord and vestibular nuclei are integration areas for the visual, vestibular and neck proprioceptor input, while the superior and inferior colliculus are integrative structures for visual and auditory inputs, as well as the ventroposterior lateral nucleus of thalamus for vestibular and neck proprioceptor input and the cervical spinal cord, cerebellum, reticular formation, temporal cortex and parietal cortex for the visual, vestibular, neck proprioceptor and auditory inputs. The cervical spinal nerves, tectospinal and vestibulospinal tracts are important in postural control, in addition to which the spinocerebellar, vestibulocerebellar and tectocerebellar tracts are crucial for postural maintenance. The medial lemniscus, medial longitudinal fasciculus, ventral acoustic stria and pathway from the superior colliculus to the reticular formation are also involved in controlling posture. The lateral lemniscus, the tract from the cochlear nuclei to the cervical spinal cord and that from the superior to the inferior colliculus or from the inferior to the superior colliculus, as well as the thalamocortical, geniculocortical, lateral occipital fasciculus, superior and inferior longitudinal fasciculus all play an important role in postural maintenance.

Damage to the CNS results in an inability to generate and control postural muscles for maintaining upright stance (Murray et al. 1975). However, practice or training can activate a sensory rearrangement (Brandt et al. 1981) such that the postural afferent systems are adapted depending on the remaining sensory afferent systems (Bhattacharya et al. 1990). In this study the effects of various sensory inputs, either individually or in various combinations, were observed to overlap in providing postural control. It is, therefore suggested that even though a sensory input system may be defective, posture can still be maintained. It is suggested that the structures, areas and pathways involved in postural control shown in Figure 12.1 are subject to future investigation by observing postural sway behaviour in association with specific structural lesions in neurological patients. If the pathways involving postural control can be established, this will be beneficial in postural rehabilitation and maintenance. Furthermore, the various interactions investigated in the present study could be extended to include the young and old.

12.2 Conclusion

1. The individual and interactive effects of visual, vestibular, neck proprioceptor and auditory inputs all influence postural maintenance.

2. Visual feedback acts as a stabilising influence, whereas vestibular, neck proprioceptor and auditory feedback have both stabilising and destabilising effects.

3. The various sensory input interactions cause both stabilisation and destabilisation of posture:
    - The visual-vestibular interaction displays both stabilising and destabilising effects on postural maintenance, with agreement appearing to depend on both the visual and vestibular systems.
    - The visual-neck proprioceptor interaction has a destabilising effect on posture, with the effect appearing to be due to summation of the visual and neck proprioceptor inputs.
    - The visual-auditory interaction appears to control the mediolateral COG projection and mean sway velocity, including both mediolateral and anteroposterior directions separately.

- The vestibular-neck proprioceptor interaction with static stimulation causes mediolateral and anteroposterior postural destabilisation, while dynamic stimulation leads to an increase in postural stability in the anteroposterior direction.
- The vestibular-auditory interaction with static vestibular input causes postural stabilisation in the anteroposterior direction, which depends on the nature of the auditory input. With dynamic vestibular stimulation the interaction leads to postural instability in both the anteroposterior and mediolateral directions with the interaction depending on the vestibular input.
- The neck proprioceptor-auditory interaction has both stabilising and destabilising effects on posture, showing anteroposterior stability and mediolateral instabilty. The interaction appears to be due to the summation between neck proprioceptor and auditory inputs, but also depends on the nature of the auditory input.
- The visual-vestibular-neck proprioceptor interaction influences posture in the anteroposterior direction, with visual input appearing to be the stabilising influence reducing the mismatch between the vestibular and neck proprioceptor systems.
- The visual-vestibular-auditory interaction influences posture in the mediolateral direction, with visual feedback acting as the stabilising factor.
- The visual-neck proprioceptor-auditory interaction influences posture in the anteroposterior direction and depends on neck proprioceptive input and auditory feedback leading to postural stabilisation.
- The vestibular-neck proprioceptor-auditory interaction with static vestibular stimulation and neck proprioceptor input causes postural stability and appears to depend on the auditory input. With dynamic stimulation the interaction leads to postural stabilisation or destabilisation depending on the vestibular and neck proprioceptor input.

- The visual-vestibular-neck proprioceptor-auditory interaction appears to control the direction of movement of the body.

4. There are no differences in postural control between static and dynamic vestibular stimulation. However, dynamic stimulation causes a greater decrease in postural stability than does static stimulation. On the other, hand there is a difference in postural control between static and dynamic neck proprioceptor stimulation leading to postural destabilisation in the mediolateral and anteroposterior directions in static stimulation, but stabilisation in only the anteroposterior direction with dynamic stimulation.

5. There is a sex difference in postural maintenance due to the dominant influence of specific sensory inputs in each gender. Vision controls sway in the mediolateral direction in males, whereas the auditory system has this role in females. The neck proprioceptor system controls the anterposterior direction in males, whereas the vestibular as well as neck proprioceptive system has this function in females.

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Appendix 1: Postural sway recording.

Postural sway behaviour was recorded using an AMTI biomechanics force plate (model OR6-5-1) connected to a six-channel signal conditioner (model SGA6-2) and linked directly on-line to a PC, which acquired, stored and subsequently analysed the signal output from the computerised biomechanics force plate system.

The computerised biomechanics force plate system

The biomechanics force plate measures the three ground reaction forces and their associated moments produced by an object in contact with the platform's surface along the XYZ axes. The three ground reaction forces are the horizontal mediolateral (Fx) and anteroposterior (Fy), and the vertical (Fz), with the associated moments being Mx and My, about the mediolateral and anteroposterior axes respectively, and Mz about the vertical axis (Figure A1.1) (AMTI 1983a).

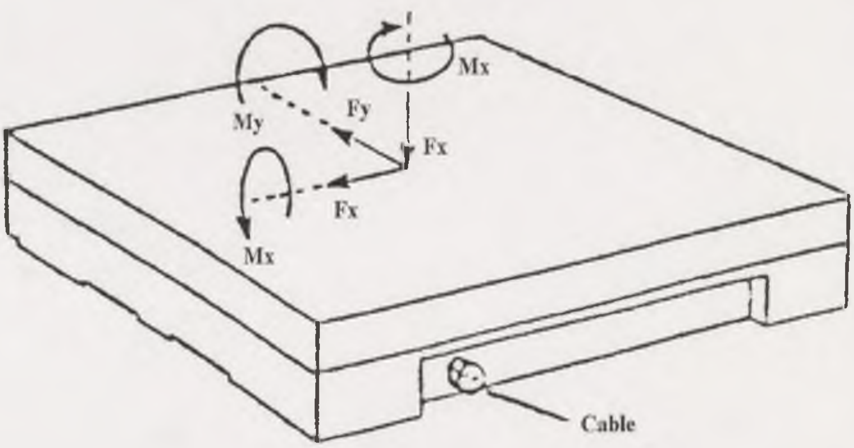


Figure A1.1 The AMTI biomechanics force plate, which measures three force and three moment components. Fx (mediolateral) and Fy (anteroposterior) are the two horizontal ground reaction forces, Fz is the vertical ground reaction force. Mx, My and Mz are the associated moments.

The true origin of the XYZ axes is located at Z, a small distance below the surface of the top plate. The three force components (Fx, Fy, Fz) of the applied force are independent of the true XYZ axes origin but their moment outputs (Mx, My, Mz) are not. If a force is applied to the top surface at any location, the moment outputs are:

$$Mx = Fx*0 - Fy*Z + Fz*Y + Tx$$
$$My = Fx*Z + Fy*0 - Fz*X + Ty$$
$$Mz = -Fx*Y + Fy*X + Fz*0 + Tz$$

where Tx, Ty and Tz are the moments applied to the top of the plate.

Normally, Tx and Ty are not applied in a physical way and Tx = Ty = 0. Then, the determination of X and Y is as follow

$$X = (Fx*Z) - My/Fz \quad \ldots\ldots\ldots\ldots\ldots\ldots 1$$
$$Y = Mx + (Fy*Z)/Fz \quad \ldots\ldots\ldots\ldots\ldots\ldots 2$$

The signal conditioner detects all applied load components at various points in the XYZ axes and sends the output from all six channels to the computer (AMTI 1982). The sensitivity output of each channel in terms of all six inputs is shown in Table A1.1 (AMTI 1983b): this sensitivity matrix refers to the true XYZ origin. Moreover, the calculated XYZ origin is at the following location relative to the top surface centre of the platform: x = 0.6mm, y = -0.2mm, z = 37.2mm.

	Mx	My	Mz	Fx	Fy	Fz
Mx′	.648	-.001	.007	.001	-.001	.000
My′	.001	.647	-.008	-.000	-.000	-.000
Mz′	-.002	-.001	1.339	-.001	.001	-.000
Fx′	-.003	.003	.005	.339	-.000	.001
Fy′	-.002	.001	-.005	-.002	.336	.000
Fz′	-.001	.000	-.000	-.001	-.001	.088

Table A1. 1 The sensitivity matrix of each channel output Mx', My', Mz', Fx', Fy' and Fz' in microvolts/volt of excitation time: mechanical input in newton-metre or newton.

References

Advanced Mechanical Technology Inc. (1983a), Model OR6-5-1 and OR6-5-6 Instruction Manual 1-2.

Advanced Mechanical Technology Inc. (1982), Model SGA6-1 Strain Gage Amplifier System 2.1-2.3.

Advanced Mechanical Technology Inc. (1983b), Calibration Data Model OR6-5-1 Biomechanics Platform Serial Number 3073 1983; C2-C3.

Appendix 2: Data acquisition and analysis.

Data acquisition and storage

The analogue data from the amplifier were acquired and stored using DT VEE software (Data Translations 1995a-e). 'Posture' was the programme written to acquire, manipulate, store and send data to Microsoft Excel (Frontline Systems, 1993) for subsequent analysis (Figure A2.1).

The 'Analogue/Digitise Configuration' object (number 0, Figures A2.1 and A2.2) is the data acquisition object. In its dialogue box, six channel lists are built at the same gain, rate and time (gain = 4, rate = 50Hz, time = 20 seconds) to collect the data from the force plate.

Posture: A/D Config (0)

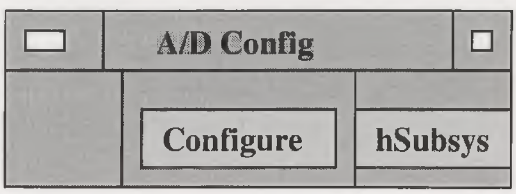


Figure A2.2 An open view of the 'Analogue/Digitise Configuration' object.

To begin analogue data acquisition the six 'Get Data Panel' objects (numbers 1 to 6, Figure A2.1) are connected to the 'Analogue/Digitise Configuration' object. In each 'Get Data Panel' object, the channel and the samples or points to be collected are specified. The six 'Get Data Panel' objects in Figure A2.1 are shown as channels 0 to 5 in Figure A2.3, and represent Fx, Fy, Fz, Mx, My, and Mz respectively: 512 samples are collected for each channel (Figure A2.3).

Posture <Network>

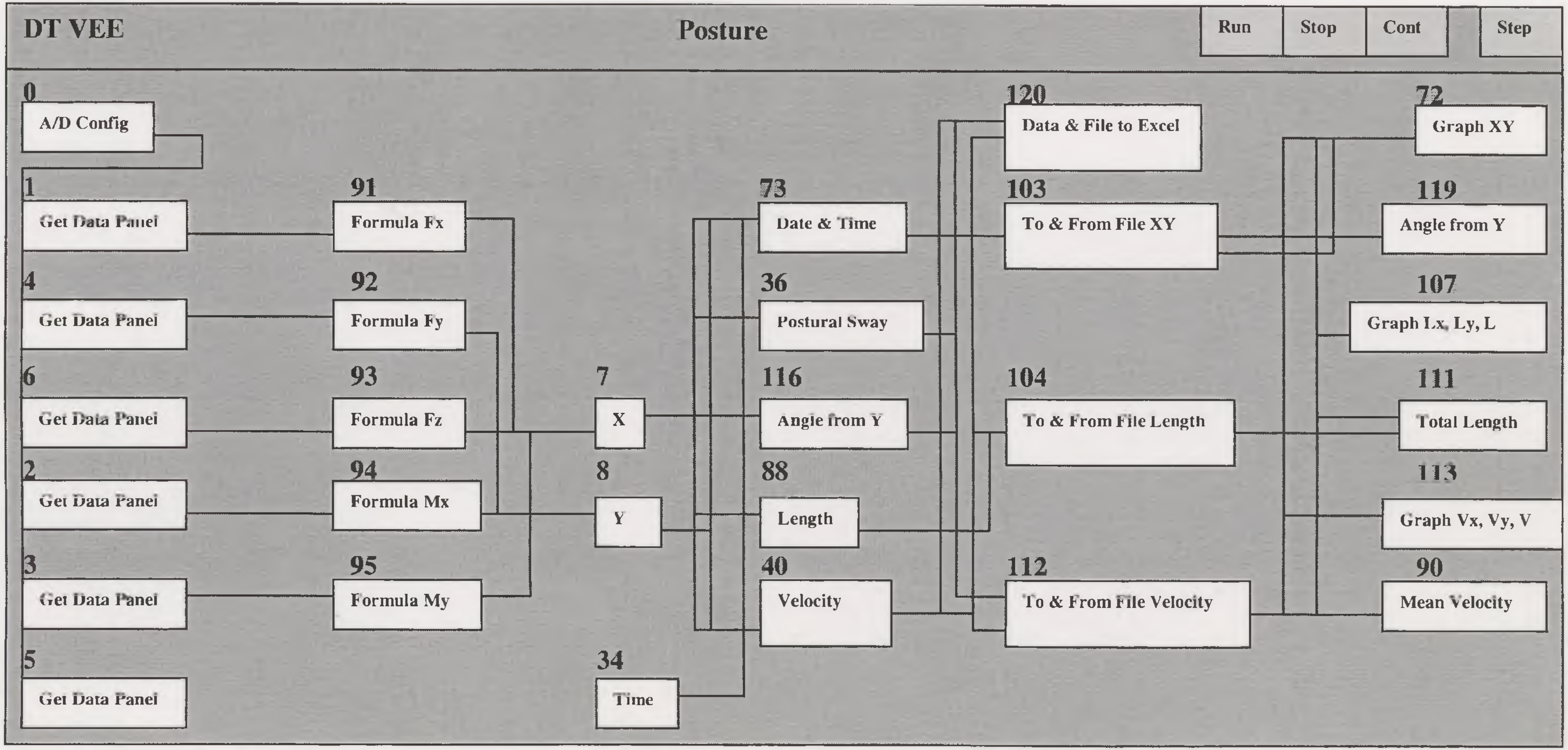


Figure A2.1 Postural scheme in DT VEE Programme which acquires, stores, retrieves and sends data to Microsoft Excel Programme. (The object number refers to the number in brackets for Figures A2.2 to A2.23).

Posture: Get Data Panel (1-6)

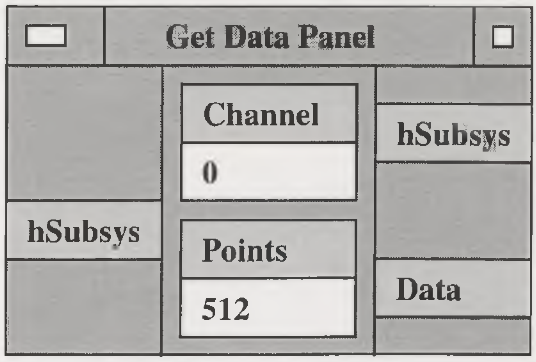


Figure A2.3 An open view of the 'Get Data Panel' object where the channel is indicated by the number 0-5 for the object 'Get Data Panel' number 1, 4, 6, 2, 3 and 5 and represent Fx, Fy, Fz, Mx, My and Mz respectively: each object collects 512 samples.

The 'Formula Fx, Fy, Fz, Mx and My' objects (number 91-95, Figure A2.1) are created to obtain the most accurate data for use in the determination of the X, Y coordinates of the centre of gravity projection. As shown in Figure A2.4, the 'Formula Fx, Fy, Fz, Mx and My' objects receive the data as A, B, C, D and E respectively with the data in each formula being multiplied by its sensitivity (Table A1.1).

To determine the values of X and Y, the objects of 'X' and 'Y' (numbers 7 and 8 respectively, Figure A2.1) are built. As stated earlier, the values of X and Y are resolved according to equations 1 and 2 given in Appendix 1. Then, by substituting Fx, Fy, Fz, Mx and My with A, B, C, D and E, together with replacing the value of Z (37.2 mm), X and Y can be determined as shown in the equation in Figure A2.4.

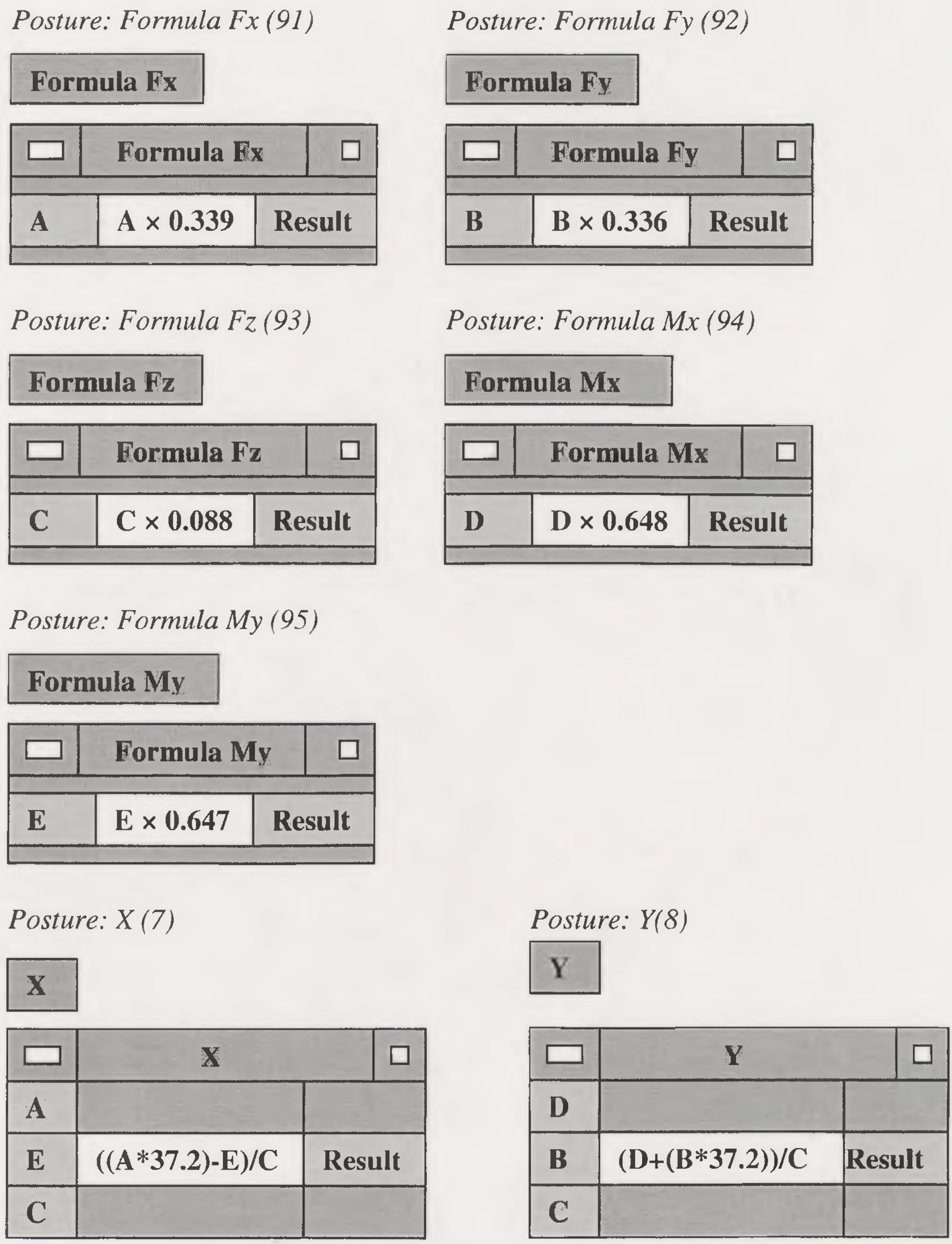


Figure A2.4 **An open view of the 'Formula Fx, Fy, Fz, Mx, My and the 'X and Y' objects. The data input in the 'Formula Fx, Fy, Fz, Mx and My' object is A, B, C, D and E is multiplied by its sensitivity given in Table A1 (Appendix 1). The result of each object is entered into the formula in the 'X and Y' object.**

When the 512 values, determined by the sampling rate and length of the data acquisition period, of X and Y have been calculated they are placed into the 'Postural Sway' object (number 36, Figure A2.1). Here the X and Y data are built into a record by the 'Build Record' object and subsequently extracted by the 'Get Field' objects (Figure A2.5). Following which the 512 X and Y values are written into file XY by the 'To File XY' object, which is located in the 'To & From File XY' object (number 103, Figures A2.1 and A2.6). The X and Y values can be viewed as an X-Y plot, using the 'XY' object, and a frequency analysis performed, using the 'Frequency Analysis' object (Figure A2.7), both of which are located in the 'Graph XY' object (number 72, Figure A2.1).

Posture: postural sway (36)

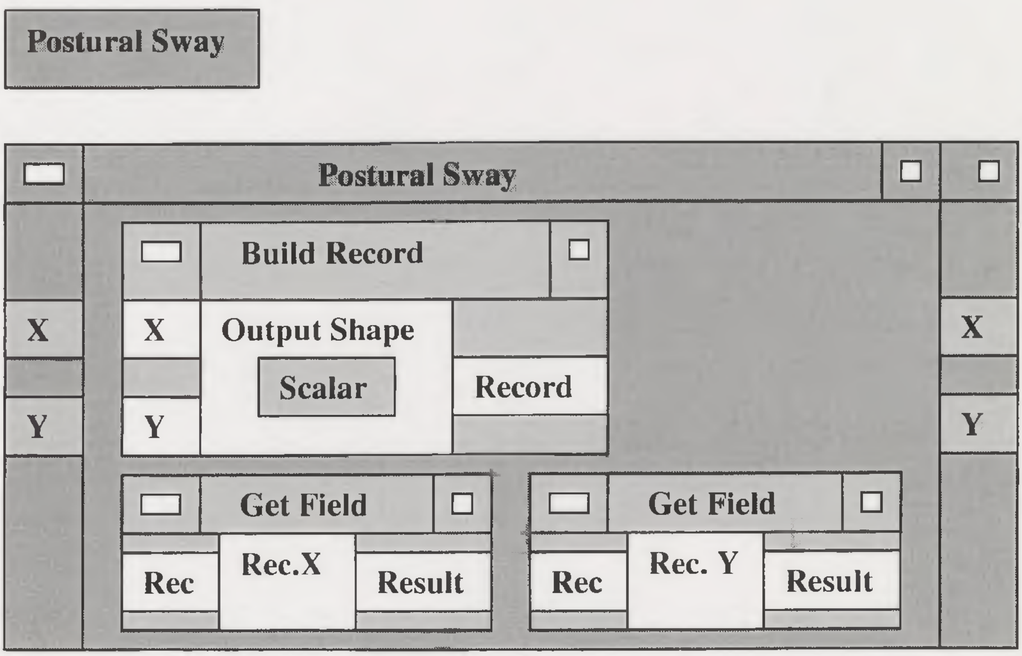


Figure A2.5 An open view of the 'Postural Sway' and the 'Build Record' objects; the latter builds the input, X and Y value, in scalar shape output. The output is changed into an array by the 'Get Field' object.

The 'Angle from Y' object (number 116, Figure A2.1) determines the angle of sway with respect to the Y-axis of the force plate, using the formula atan(X/Y) in the 'atan(AY)' object (Figure A2.8): the 'Ary AY' object (Figure A2.8) displays all 512 values. The mean value of this angle is calculated using the 'Sum (AY)' object whose output is transferred into the 'Mean (AY)' object (Figure A2.8) and divided by 512. The mean value of the angle of sway is written into file XY using the 'To File XY' located in the 'To & From File XY' object (number 103, Figures A2.1 and A2.6): the mean value is shown in the 'AY' object (Figure A2.9) in the 'Angle from Y' object (number 119, Figure A2.1).

Posture: To & From File XY (103)

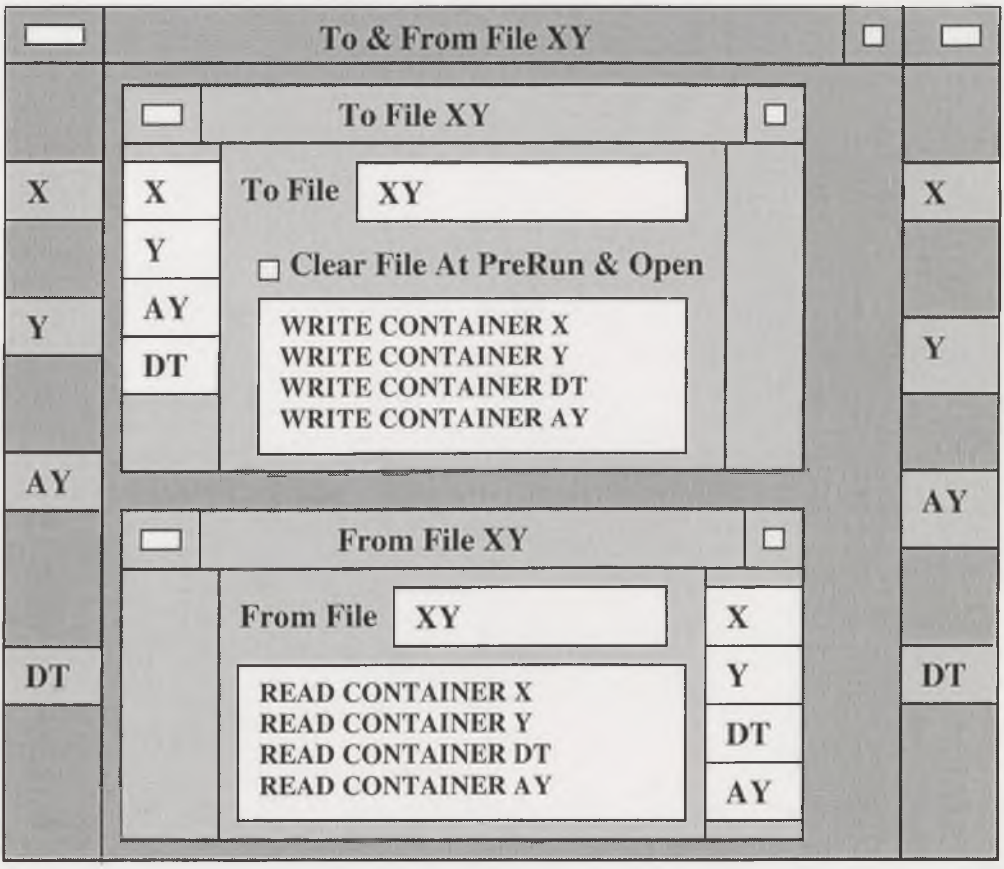


Figure A2.6 An open view of the 'To & From File XY' object. The 'To File XY' object writes the input data of X, Y, the angle of sway from Y (AY) and the date and time of the data collection (DT) into file XY. The 'From File XY' object reads the data from file XY. The 'To File XY' is connected to the 'From File XY' by the sequence output and input pin.

Posture: Graph XY (72)

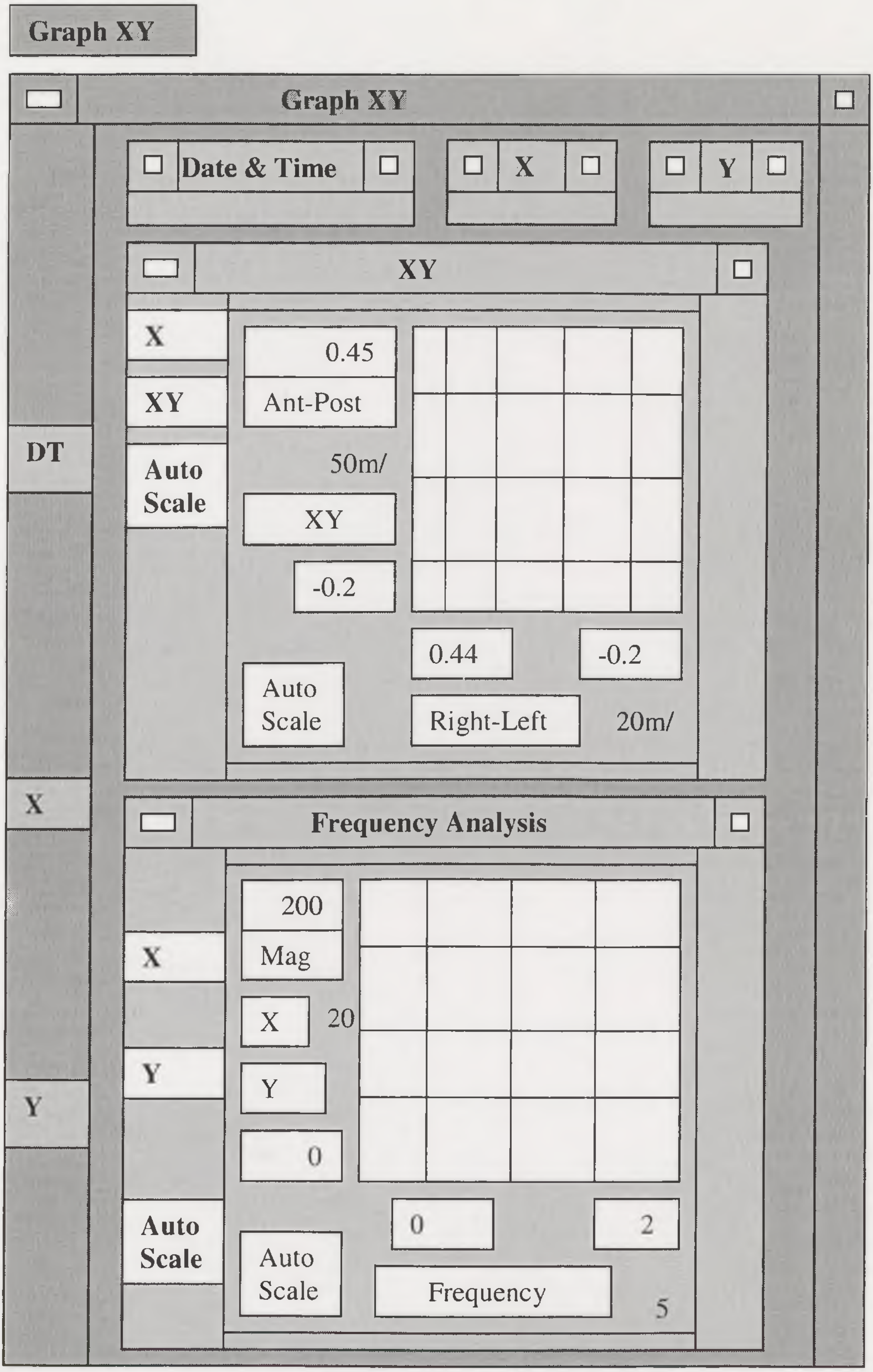


Figure A2.7 **An open view of the 'Graph XY' object. The X and Y data is plotted in the 'XY' object and its frequency content is plotted in the' Frequency Analysis' object. The recorded date and time is presented in the 'Date & Time' object.**

Posture: Angle from Y (116)

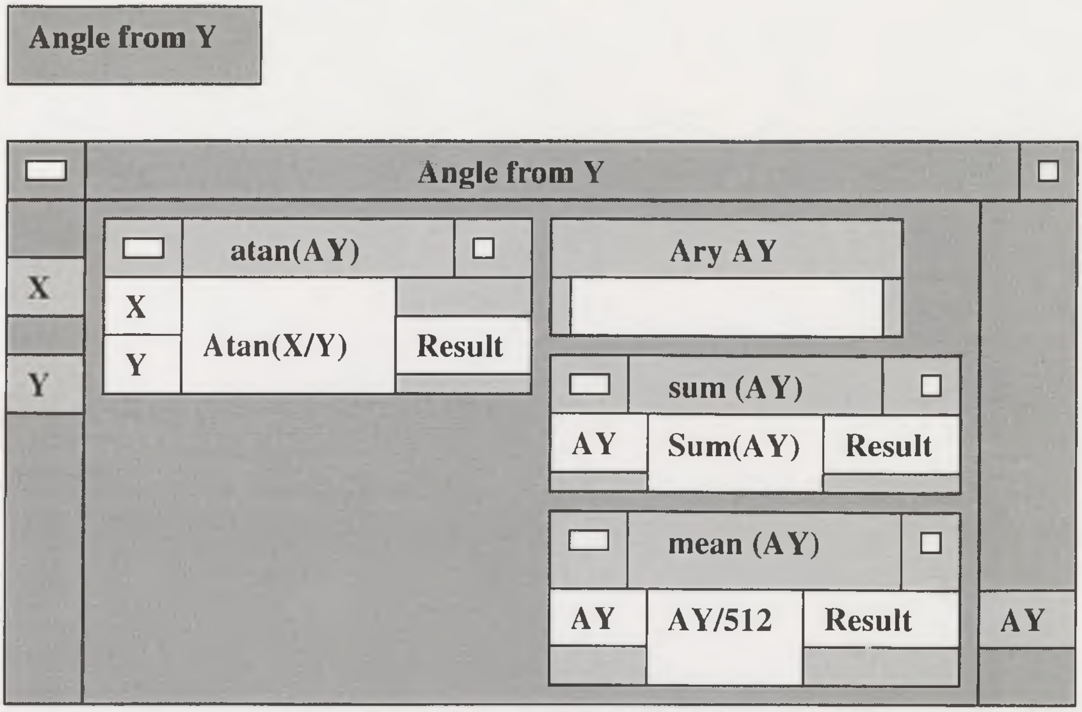


Figure A2.8 An open view of the 'Angle from Y' object. The 'atan(AY)' object is the formula object which calculates the angle of sway from the Y-axis. The 512 values are displayed in the 'Ary AY' object and sent to the 'sum (AY)' object and then to the 'mean (AY)' object.

Posture: Angle from Y (119)

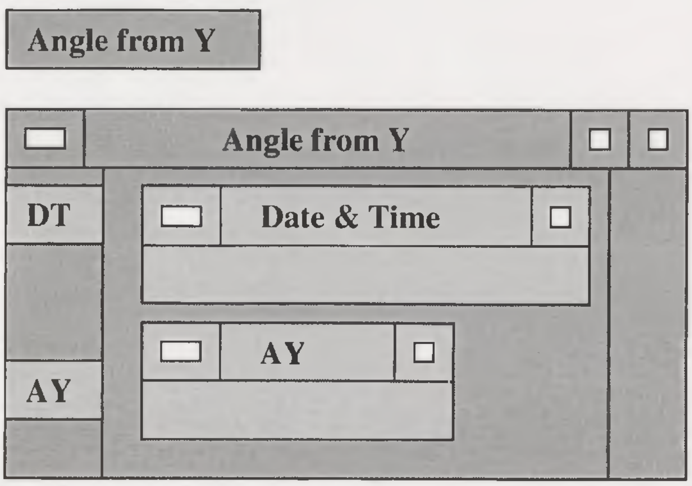


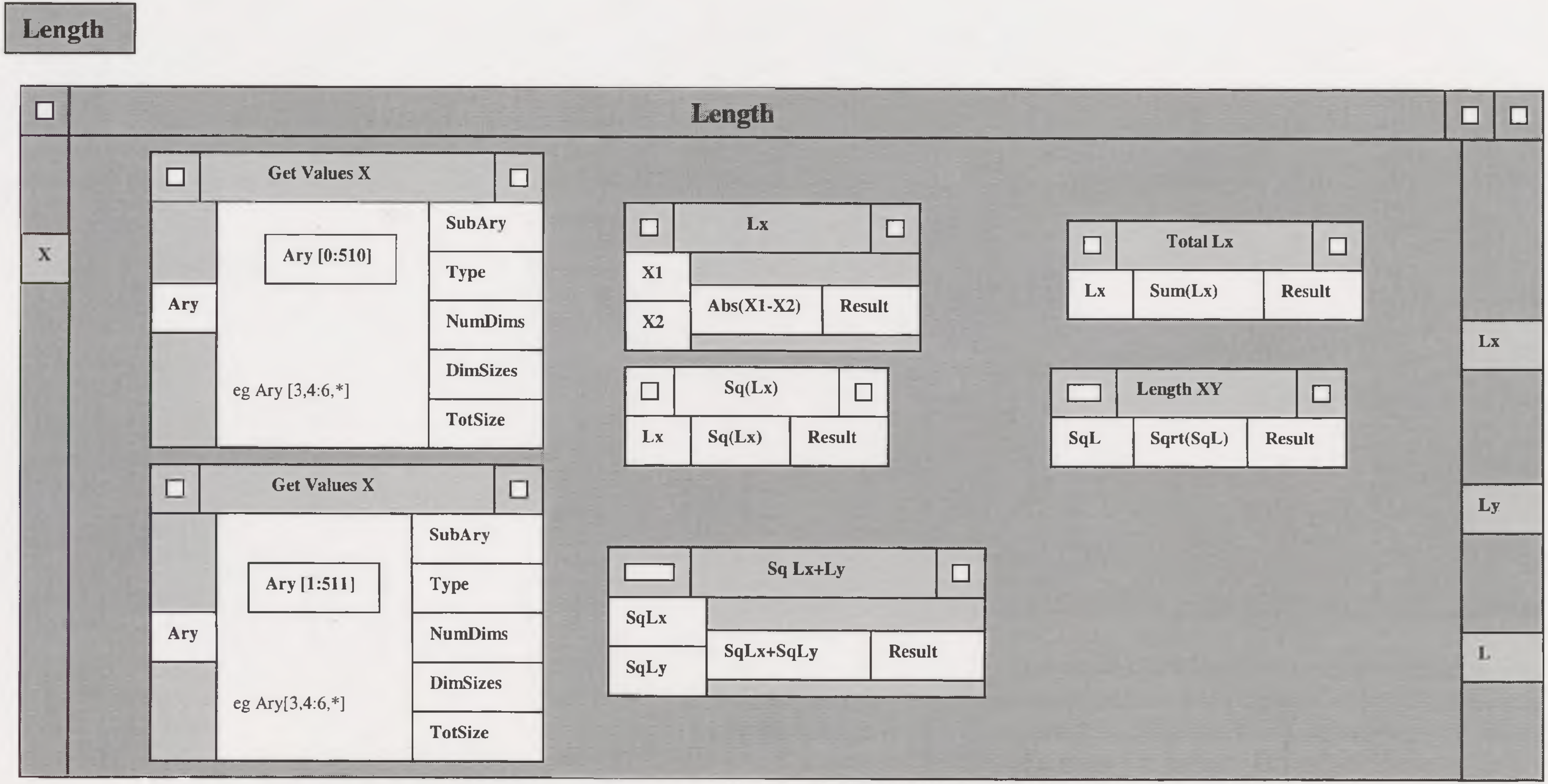
Figure A2.9 An open view of the 'Angle from Y' object. The mean value of the angle of sway from the Y-axis is present in the 'AY' object. The recorded date and time is shown in the ' Date & Time' object.

Using the 512 calculated values of X and Y, the distance between successive points, i.e. length, in the X and Y directions, Lx and Ly respectively, as well as the true distance between successive pairs of coordinates, L, are determined. All lengths are calculated using the 'Length' object (number 88, Figure A2.1): Lx and Ly from the formula given in the 'Lx and Ly' object and L by the formula given in the 'Length XY' object (Figure A2.10). The resulting 511 values for each variable are recorded in file L using the 'To File Length' object (Figure A2.11) located in the 'To & From File Length' object (number 104, Figure A2.1). The 511 values of Lx, Ly and L can be read from the 'From File Length' object (Figure A2.11), and displayed as an array of numbers in the 'Lx, Ly and L' object (Figure. A2.12), or plotted against time in the 'Length' object (Figure A2.12) located in the 'Graph Lx, Ly, L' object (number 107, Figure A2.1).

In addition the total path length in the X and Y directions is calculated, TLx and TLy, as well as the total true path length, TL, using the 'Total Lx', 'Total Ly' and 'Total Length' objects respectively (Figure A2.10). These values are then written into file L by the 'To File Length' object (Figure A2.11) located in the 'To & From File Length' object (number 104, Figure A2.1). Using the 'From File Length' object (Figure A2.11) the values of TLx, TLy and TL can be displayed in the 'TLx, TLy and TL' object (Figure A2.13) located in the 'Total Length' object (number 111, Figure A2.1).

The velocity of sway can be determined from the distance moved divided by time taken, which is constant and set by the sampling rate. In the Postural programme the 'Time' object (number 34, Figure A2.1) is set to collect 512 samples in 20 seconds, thus the time between successive samples is 0.039 seconds. Time Ti (Figure A2.15) is conveyed to the 'Velocity' object (number 40, Figure A2.1).

Posture: Length (88)



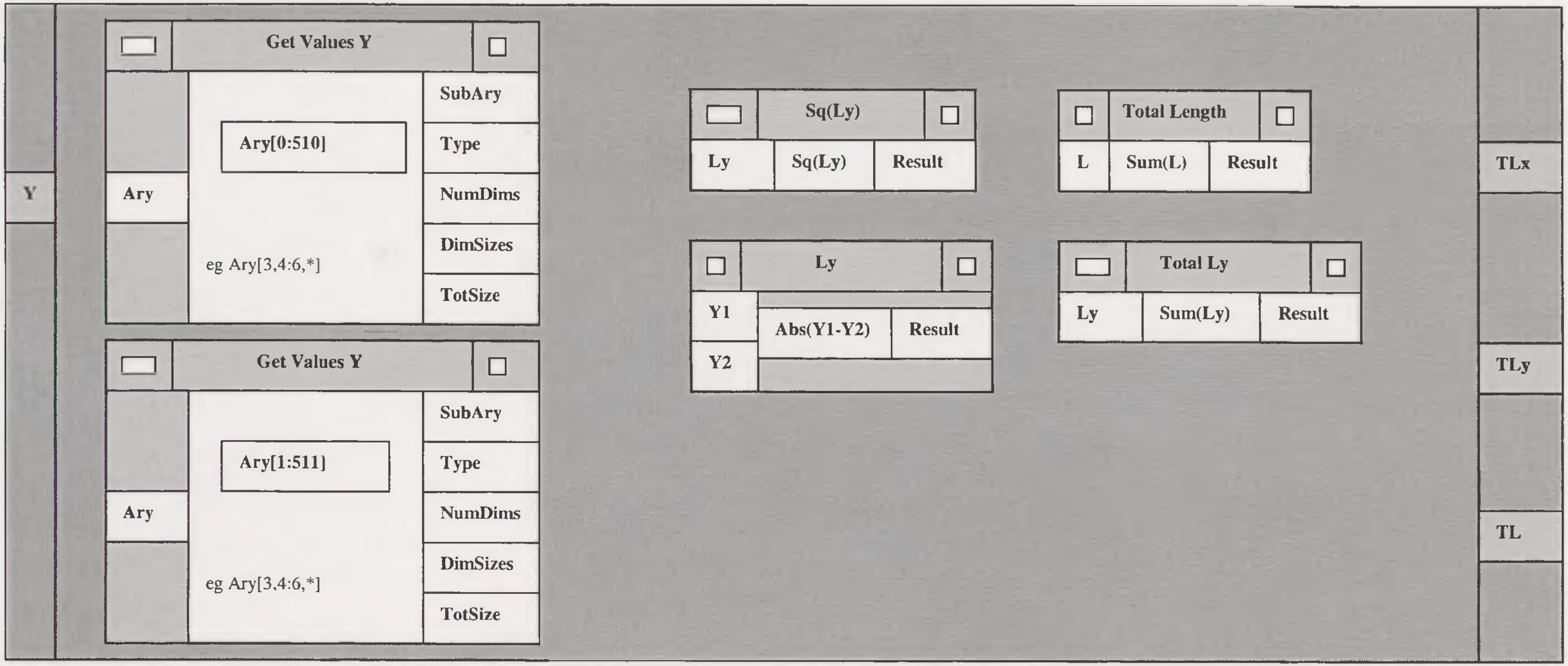


Figure A2.10 **An open view of the 'Length' object. The 512 values of X and Y are extracted by the 'Get Values X and Y' object and used in the calculations of the 'Lx and Ly' object. The output from the 'Lx and Ly' object is multiplied by its value in the 'sq (Lx)' and 'sq (Ly)' objects. The result from the 'sq (Lx)' and 'sq (Ly)' object is summed in the 'sq Lx + Ly' object. The output of the 'Lx', 'Ly' and 'Length XY' objects is used to determine to total lengths in the 'Total Lx', 'Total Ly' and 'Total Length' object.**

Posture: To & From File Length (104)

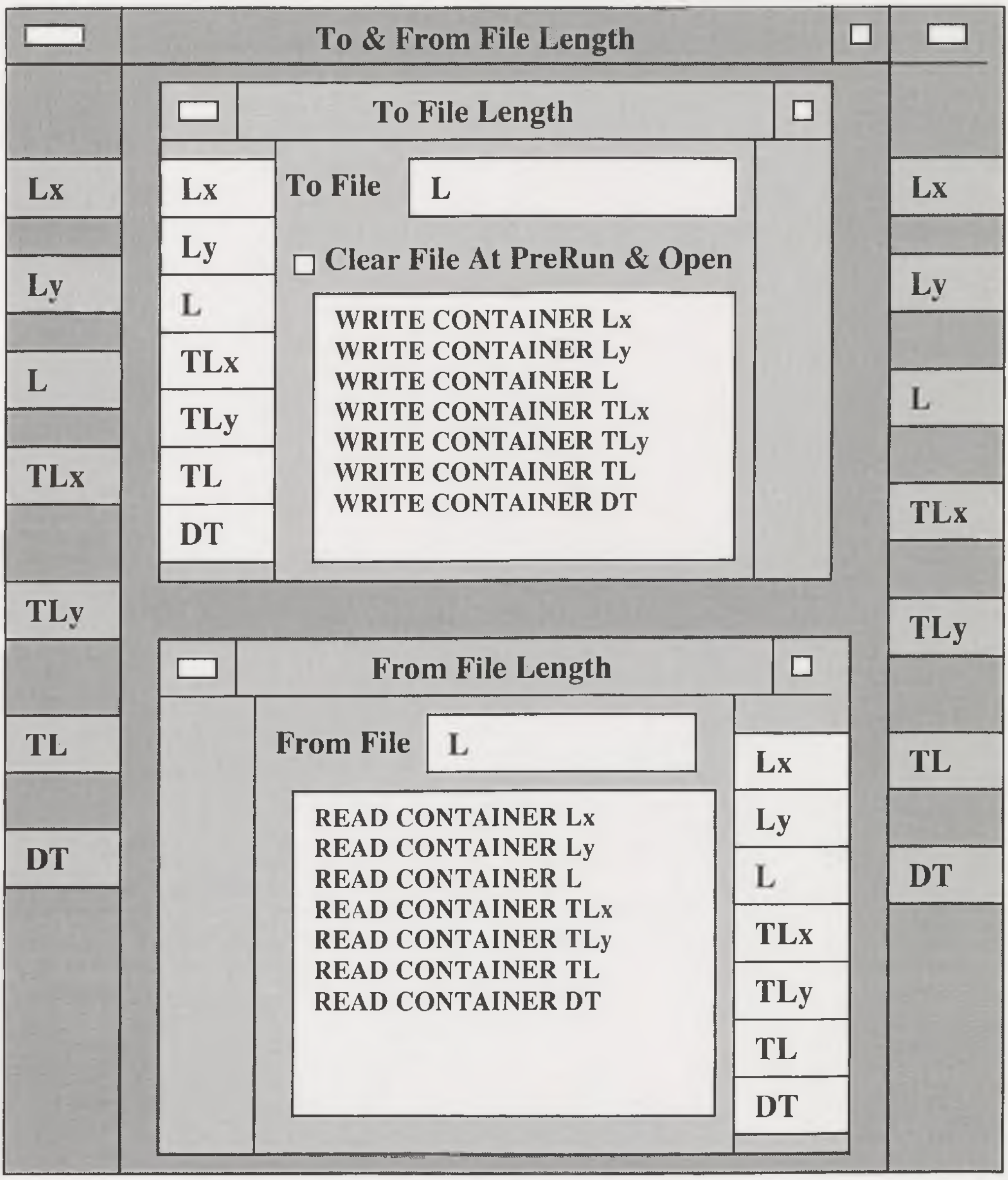


Figure A2.11 An open view of the 'To & From File Length' object. The 'To File Length' object writes the input data of each successive length Lx, Ly and L together with TLx, TLy and TL and the date and time of the data collection, DT, into file L. The 'From File Length' object reads the data from file L. The ' To File Length' object is connected to the ' From File Length' by the sequence output and input pin.

Posture: Graph Lx, Ly, L (107)

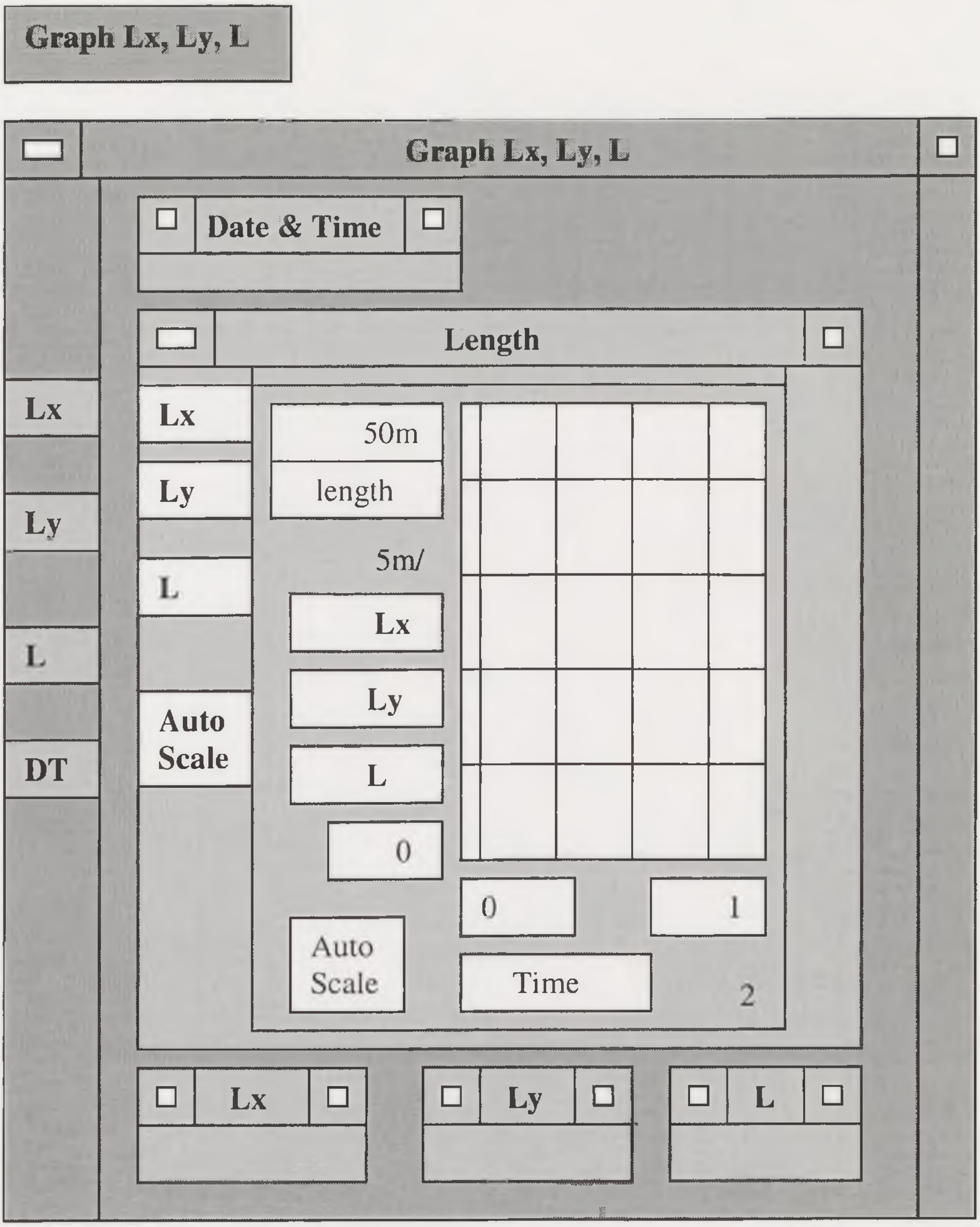


Figure A2.12 An open view of the ' Graph Lx, Ly, L' object. The each successive Lx, Ly and L value is plotted against time in the 'Length' object. The recorded date and time is displayed in the 'Date & Time' object.

Posture: Total Length (111)

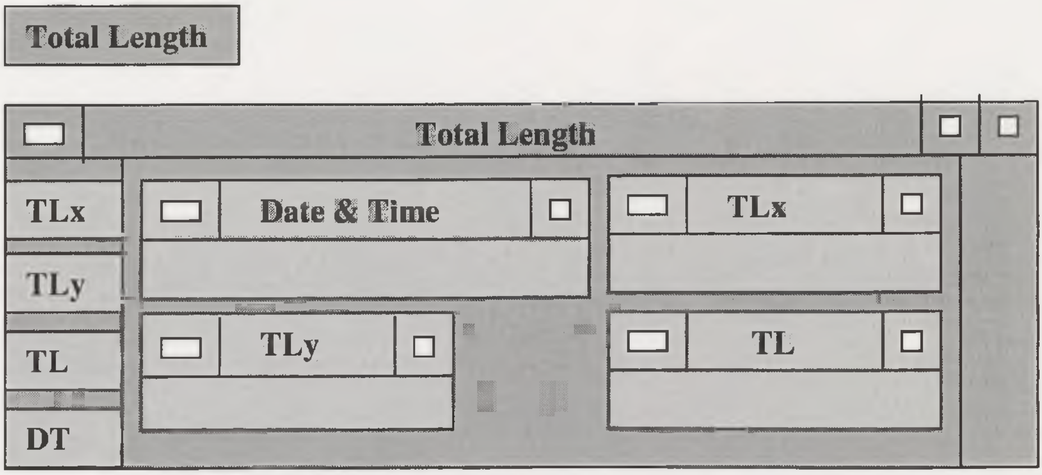


Figure A2.13 An open view of the 'Total Length' object. The 'TLx', 'TLy' and 'TL' objects display the number in its object. The recorded date and time is displayed in the 'Date & Time' object.

The 'Velocity' object (number 40, Figure A2.1) enables the velocity of movement in the X and Y directions and the true velocity, Vx, Vy and V respectively, to be calculated, as well as the mean values of each of these velocities, Vxm, Vym and Vm. The instantaneous velocities Vx, Vy and V are calculated by dividing Lx, Ly and L by time Ti in the 'Velocity X', 'Velocity Y' and 'Velocity XY' objects (Figure A2.14) in the 'Velocity' object (number 40, Figure A2.1). The mean of the 511 values is determined using the formula in the 'Mean (Vx)', 'Mean (Vy)' and 'Mean (V)' objects (Figure A2.14), and the results recorded in file V by the 'To File Velocity' object (Figure A2.15) located in the 'To & From File Velocity' object (number 112, Figure A2.1). The instantaneous values can be retrieved using the 'From File Velocity' object (Figure A2.14) located in the 'To & From File Velocity' object (number 112, Figure A2.1) and displayed using the 'Vx, Vy and V' object, or plotted using the 'Graph Vx, Vy, V' object (number 113, Figure A2.1; Figure A2.16). The mean values can be displayed using the 'Vxm, Vym and Vm' object (number 90, Figure A2.1; Figure A2.17).

The 'Date & Time' object (number 73, Figure A2.1) shows the day, date, month and year, and the time in hours, minutes and seconds at which a particular recording of postural sway was made. By accessing the date and time the 'now()' object (Figure A2.18) is selected (Data Translations 1995b) and connected to the

'To String' object (Figure A2.18) in order to write the date and time of the recording to the data file.

Posture: Velocity (40)

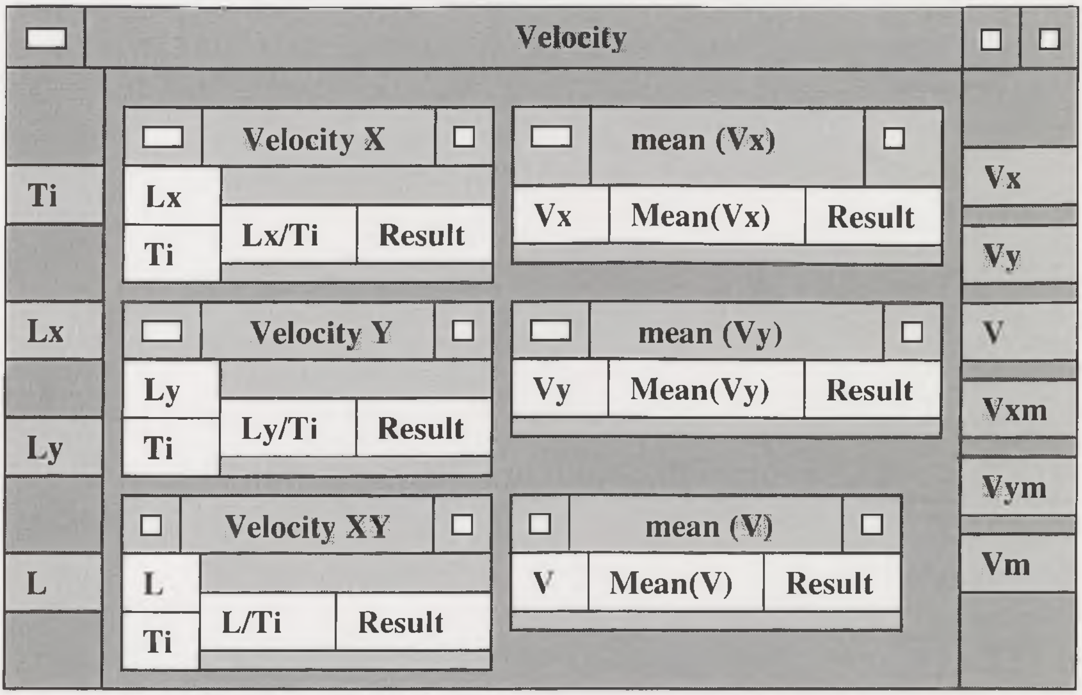


Figure 2.14 **An open view of the 'Velocity' object. The instantaneous velocities Vx, Vy and V are calculated from the successive lengths divided by the time between samples, determined from the 'Time' object, and is shown in the 'Velocity X', 'Velocity Y' and 'Velocity XY' objects. The values are averaged in the 'mean (Vx)', 'mean (Vy)' and 'mean (V)' objects to give Vxm, Vym and Vm respectively.**

Posture: To & From File Velocity (112)

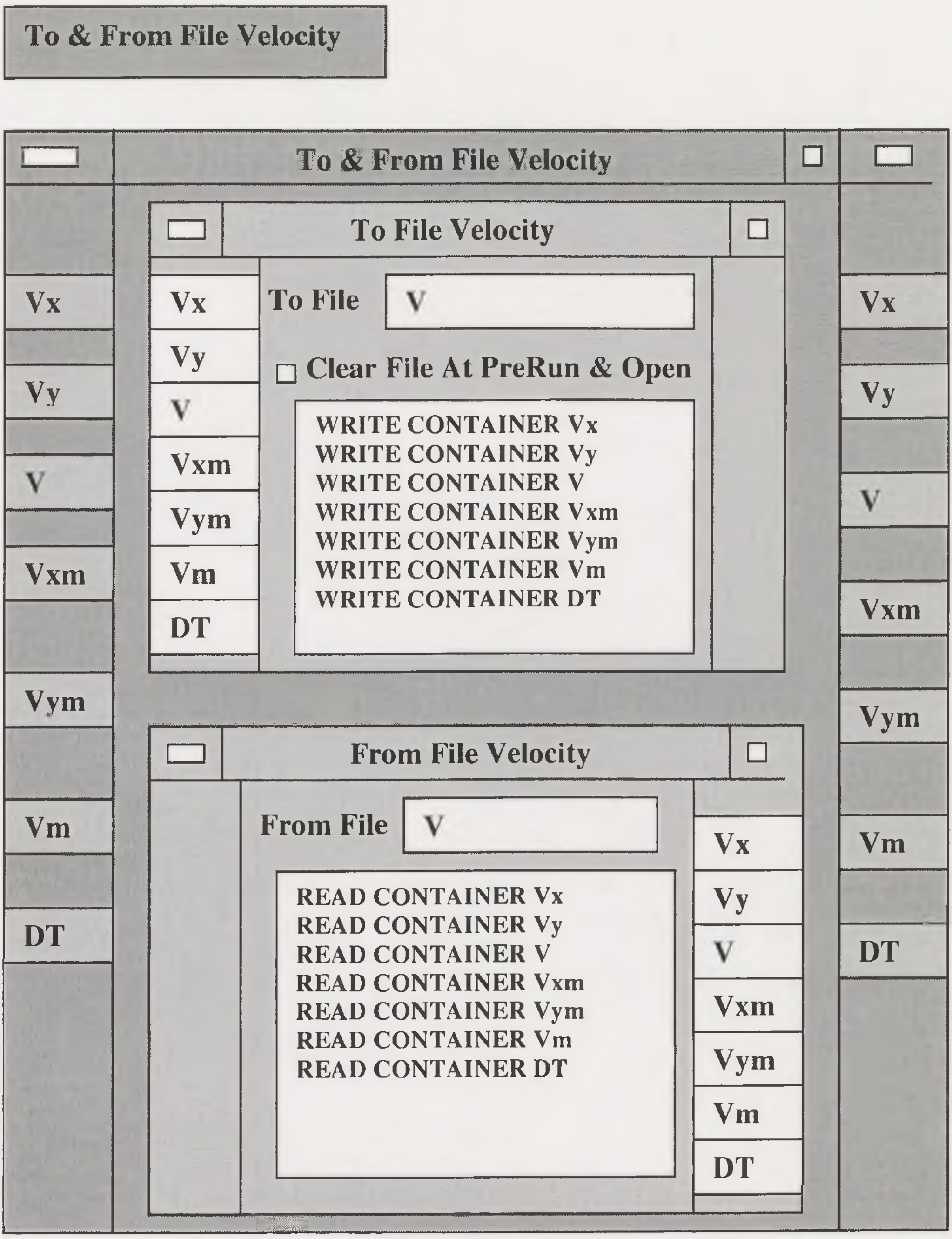


Figure A2.15 An open view of the 'To & From File Velocity' object. The 'To File Velocity' object writes the instantaneous velocity Vx, Vy and V as well as Vxm, Vym and Vm and the date and time of the data collection, DT, into file V. The 'From File Velocity' object reads the data from file V. The ' To File Velocity' object is connected to the ' From File Velocity' by the sequence output and input pin.

Posture: Graph Vx, Vy, V (113)

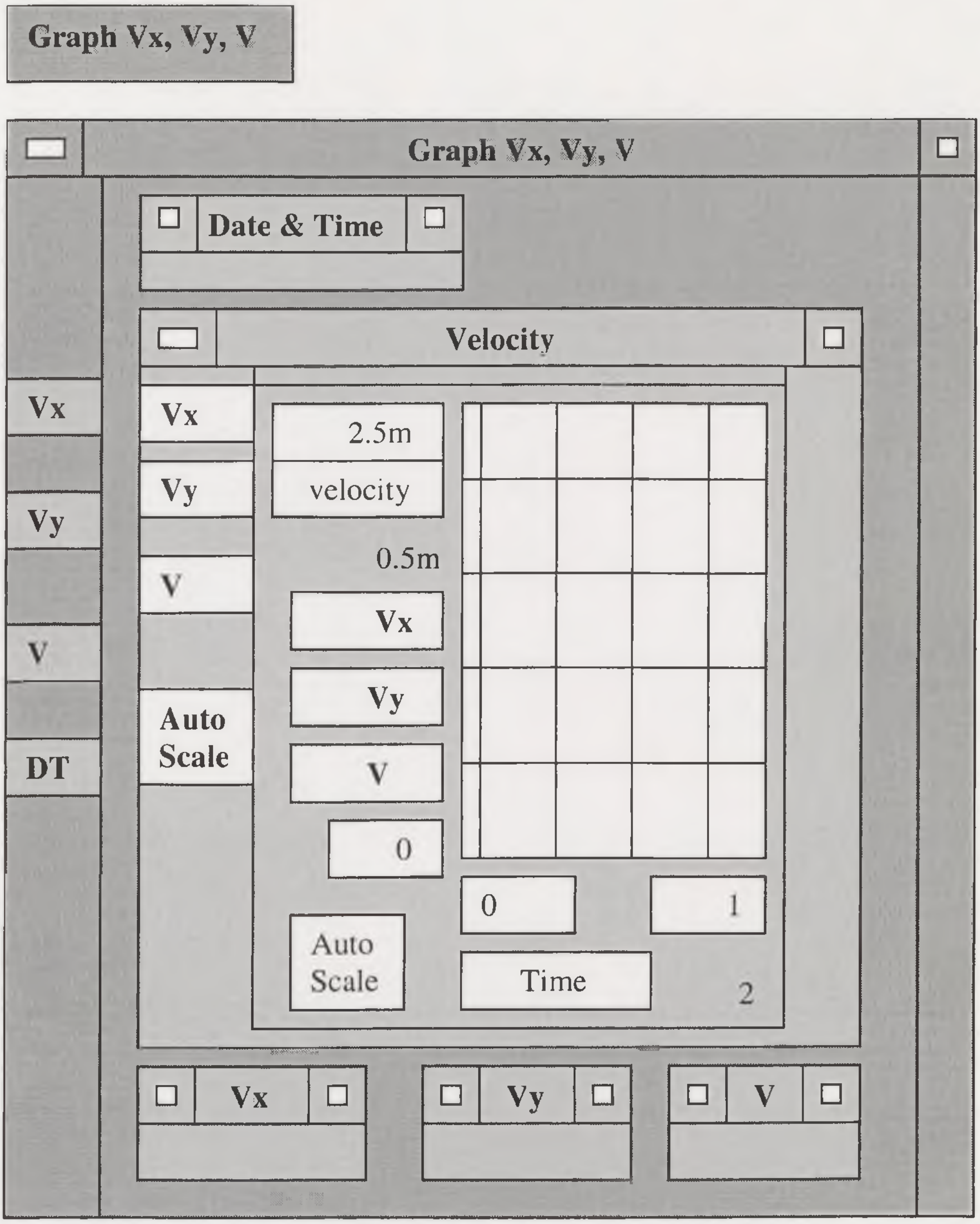


Figure A2.16 An open view of the ' Graph Vx, Vy, V' object. Each instantaneous Vx, Vy and V value is plotted against time in the 'Velocity' object. The recorded date and time is displayed in the ' Date & Time' object.

The date and time is recorded and retrieved by the 'To & From file XY' object (number 103, Figure A2.1; Figure A2.6), the 'To & From File Length' object (number 104, Figure A2.1; Figure A2.11) and the 'To & From File Velocity' object (number 112, Figure A2.1; Figure A2.16), and displayed in the 'Graph XY' object (number 72, Figure A2.1; Figure A2.7), the 'Angle from Y' object (number 119, Figure A2.1; Figure A2.9), the 'Graph Lx, Ly, L' object (number 107, Figure A2.1; Figure A2.12), the 'Total Length' object (number 111, Figure A2.1; Figure A2.13), the 'Graph Vx, Vy, V' object (number 113, Figure A2.1; Figure A2.16) and the 'Mean Velocity' object (number 90, Figure; Figure A2.17).

Posture: Mean Velocity (90)

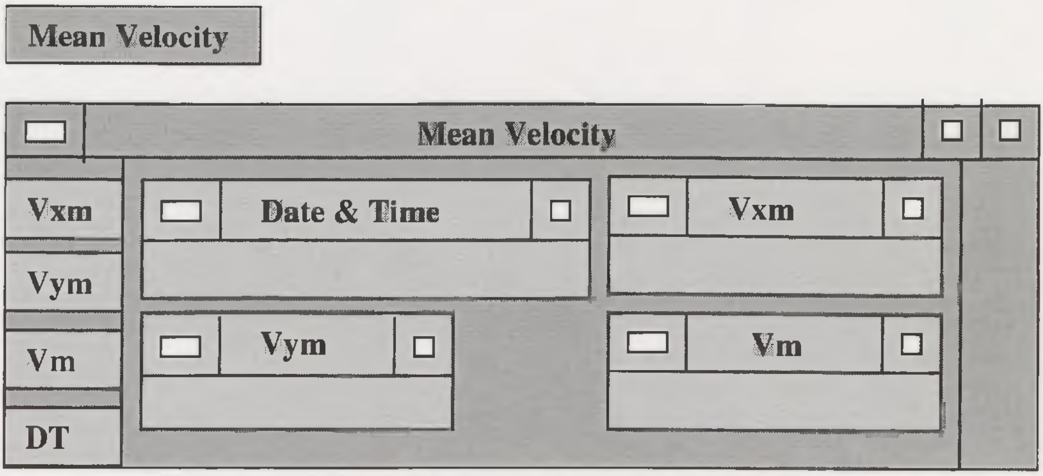


Figure A2.17 **An open view of the 'Mean Velocity' object. The 'Vxm', 'Vym' and 'Vm' objects display the number in its object. The recorded date and time is displayed in the 'Date & Time' object.**

Posture: Date & Time (73)

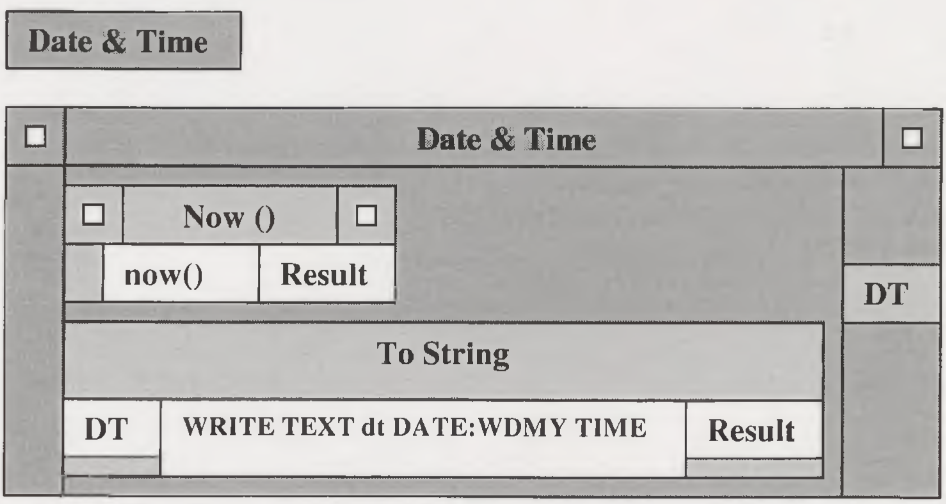


Figure A2.18 **An open view of the 'Data & Time' object. The 'now ()' object is connected to the 'To String' object to determine the time format.**

Posture: Lx 512 points (120.64), Ly 512 points (120.65), L 512 points (120.66) Vx 512 points (120.71), Vy 512 points (120.72), V 512 points (120.73)

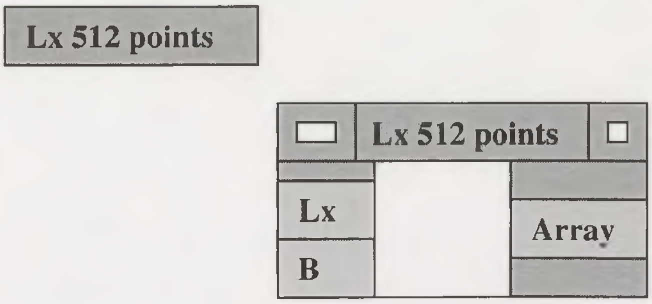
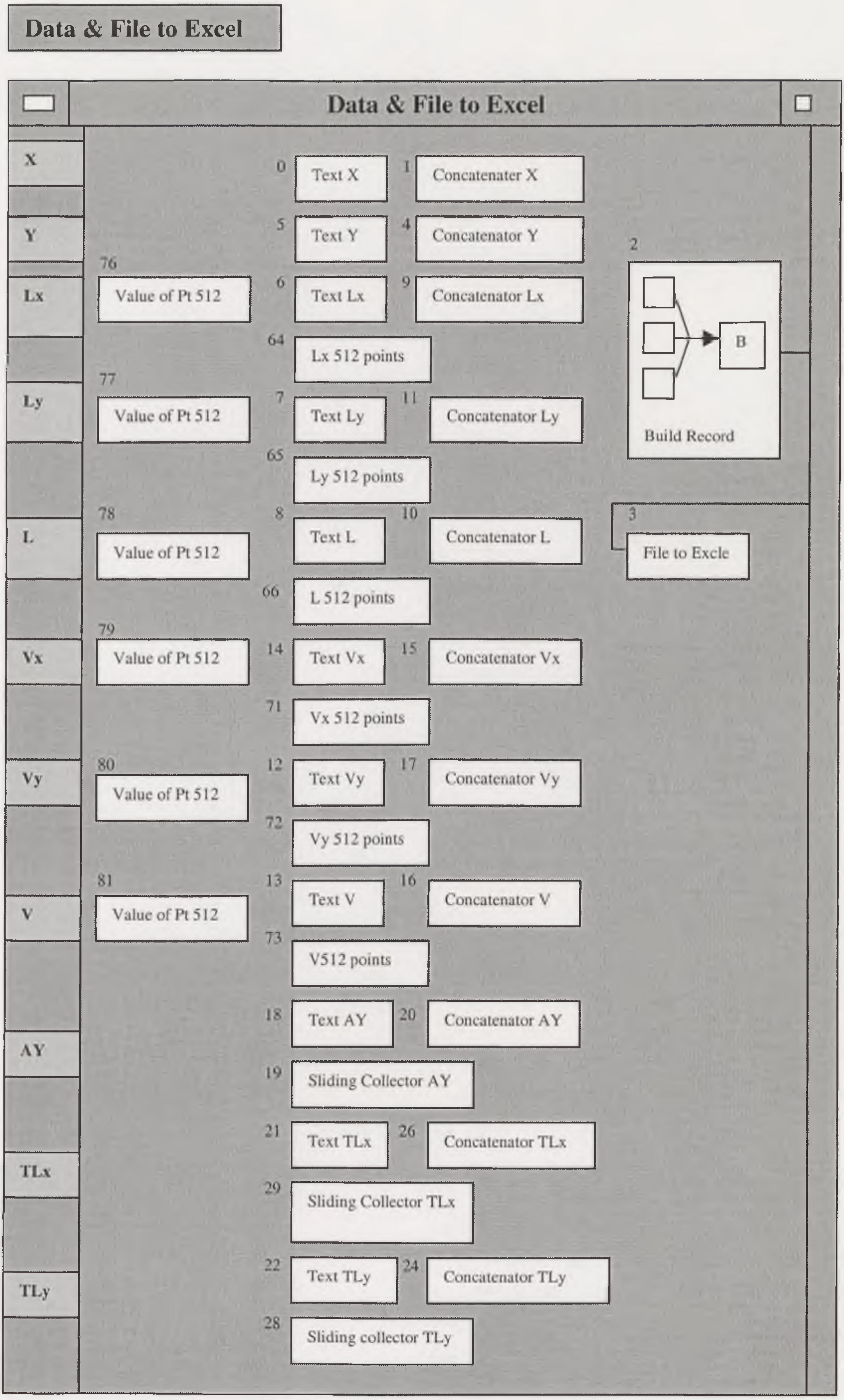


Figure A2.19 An open view of the 'Lx 512 points' object. The two input data in the object are the 511 values and 512^{th} value, the real number 0 in terms of B. An open view of the 'Ly 512 points', 'L 512 points', 'Vx 512 points', 'Vy 512 points' and 'V 512 points' objects are similar to the 'Lx 512 points' object. (The second number in brackets is the object number in Figure A2.20).

The 'To & From File XY' object (number 103, Figure A2.1), the 'To & From File Length' object (number 104, Figure A2.1) and the 'To & From File Velocity' object (number 112, Figure A2.1) are built in the postural scheme to store and retrieve data in DT VEE programmes. Moreover, all data are transferred into the 'Data & File to Excel' object (number 120, Figure A2.1; Figure A2.20) for subsequent analysis in Microsoft Excel (Frontline system 1993).

From the 512 values of X and Y and 511 values of lengths and velocities are calculated. Consequently a 512^{th} value needs to be added to complete the 512 data array, thus the real number 0 is added to the 'Value of Pt 512' object. This is achieved by connecting the 'Value of Pt 512' object to B (Figure A2.19) in the 'Lx 512 points', 'Ly 512 points', 'L 512 points', 'Vx 512 points', 'Vy 512 points' and 'V 512 points' objects (Figure A2.20). The values AY, TLx, TLy, TL, Vxm, Vym and Vm are all single values, consequently the 'Sliding Collector' object is selected (Data Translations 1995b) to set the remaining 511 values (Figure A2.20). As shown in Figure A2.21 the 'Sliding Collector' object reconstitutes the 512-array size by adding the real number 0.

Posture: Data & File to Excel (120)



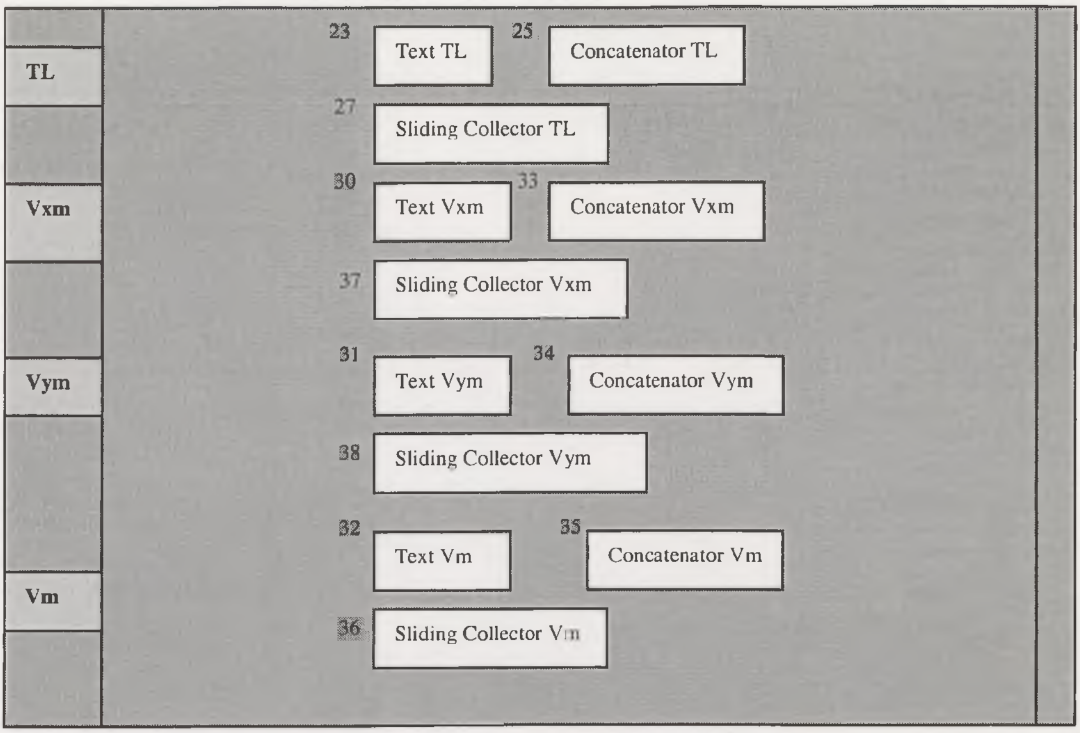


Figure A2.20 **The open view of the 'Data & File to Excel' object. The six 'Value of Pt 512' objects are linked to the Lx 512 points, Ly 512 points, Vx 512 points, Vy 512 points and V 512 points object, which each have 511 values, to build the data to 512 values. The Sliding Collector AY, Sliding Collector TLx, Sliding Collector TLy, Sliding Collector TL, Sliding Collector Vxm, Sliding Collector Vym and Sliding Collector Vm object receive its data input and build the data to the 512 values. The parameter name is put in the Text X, Text Y, Text Lx, Text Ly, Text L, Text Vx, Text Vy, Text V, Text AY, Text TLx, Text TLy, Text TL, Text Vxm, Text Vym and Text Vm object. The input of the Concatenator object of each parameter consists of the parameter name and the 512 values. The output of each concatenator object is transferred into the Build Record object and finally written in the File to Excel object.**

Posture: *Sliding Collector Ay (120.19), Sliding Collector TLx (120.29) Sliding Collector TLy (120.28), Sliding Collector TL (120.27) Sliding Collector Vxm (120.37), Sliding Collector Vym (120.38) Sliding Collector Vm (120.36)*

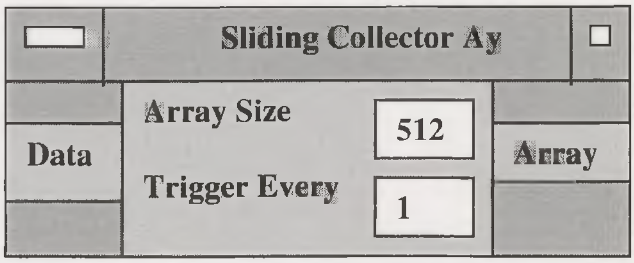
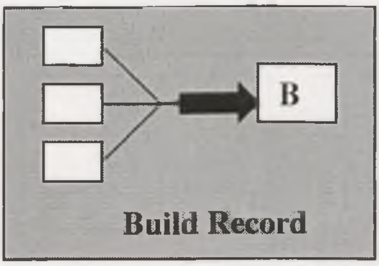


Figure A2.21 An open view of the 'Sliding Collector Ay' object. The real number 0 is triggered every step until point 512. The 'Sliding Collector TLx', 'Sliding Collector TLy', 'Sliding Collector TL', 'Sliding Collector Vxm', 'Sliding Collector Vym' and 'Sliding Collector Vm' objects are similar to the 'Sliding Collector Ay' object. (The second number in brackets is the object number in Figure A2.20).

The name of each parameter is written in the 'Text' object for each parameter and minimised as shown in Figure A2.20. The 'Concatenator' object (Figure A2.21) links the parameter name with its 512 data values. The output of each 'Concatenator' object is sent to the 'Build Record' object (Figure A2.20 and A2.22), which gives the array one dimension output shape. All data from the 'Build Record' object is written as term A into file XYLV, a Microsoft Excel spreadsheet, by the 'File to Excel' object (Figures A2.20 and A2.23).

Posture: Build Record (120.2)



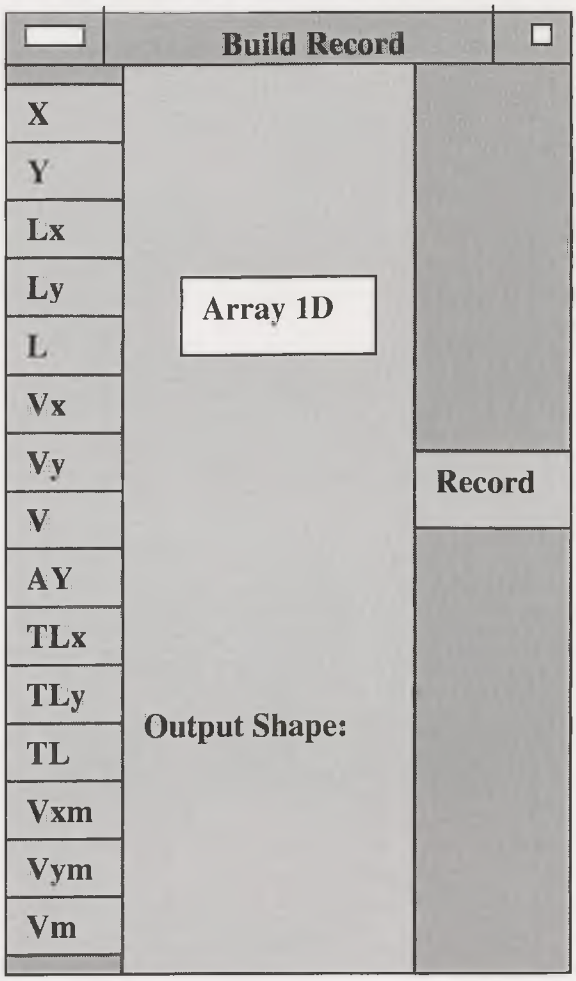


Figure A2.22 An open view of the 'Build Record' object. The data from each parameter is built into the record as a 1-dimensional array. (The second number in brackets is the object number in Figure A2.20).

Posture: File to Excel (120.3)

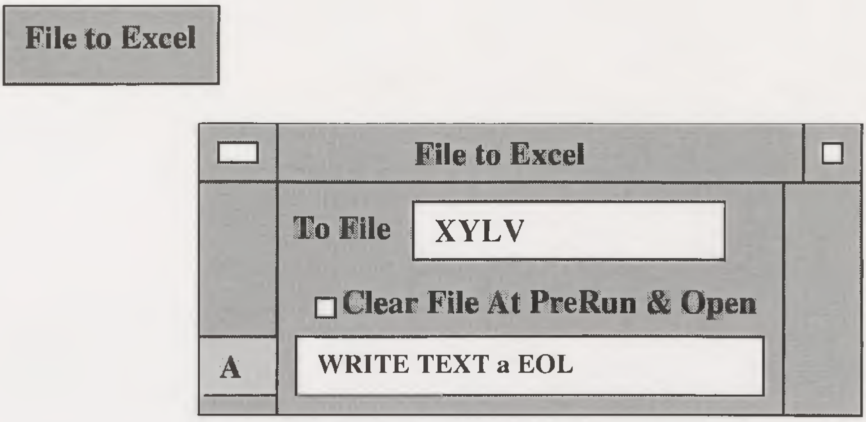


Figure A2.23 An open view of the 'File to Excel' object. A is the input data and written to file XYLV. (The second number in brackets is the object number in Figure A2.22).

Data manipulation and analysis

Firstly, the added 512th data point for the parameters Lx, Ly, L, Vx, Vy, and V together with added 511 values of Ay, TLx, TLy, TL, Vxm, Vym and Vm are removed.

Secondly, the means of the 512 values for X and Y and the 511 values Lx, Ly, L, Vx, Vy and V are determined. The mean value of X and Y represent the position of the mean centre of gravity projection of the subject on the force platform with respect to the X and Y axes. The mean values of Lx, Ly, L, Vx, Vy and V are the average lengths and velocities of movement in the X and Y direction. The values AY, TLx, TLy, TL, Vxm, Vym and Vm have already been determined using the DT VEE software, as described earlier.

Thirdly, the X and Y values which are greater or less than the mean X and Y values are averaged and added together for each direction. This gives the mean amplitude of sway in each direction; Sx in the mediolateral direction, separately either to the right (Sr) or left (Sl), and Sy in the anteroposterior direction, separately either anteriorly (Sa) or posteriorly (Sp).

Finally, the parameters X, Y, Sx, Sr, Sl, Sy, Sa, Sp, Ay, TLx, TLy, TL, Vxm, Vym, Vm, and the mean values of Lx, Ly, L, Vx, Vy and V were used in separate analyses of variance with vision, neck rotation, neck flexion/extension and auditory as well as sex as the independent variables.

References

Data Translation Inc. (1995a), Getting Started with DT VEE 3rd ed., March.

Data Translation Inc. (1995b), How to Use DT VEE 1st ed., July.

Data Translation Inc. (1995c), Building an operation Interface in DT VEE 1st ed., March.

Data Translation Inc. (1995d), Data Acquisition with DT VEE 2nd ed., July.

Data Translation Inc. (1995e), DT VEE Advanced Programming Techniques 3rd ed., March.

Frontline Systems, Inc. (1993), User's Guide Microsoft Excel Version 5.0.

Appendix 3: Class 2 laser source.

As shown in Figure A3.1 a moving spot of laser light was produced by projecting the beam from a laser presentation pointer on to a mirror mounted on a pen motor. The pen motor and mirror are controlled by channel 1 of a pen recorder (MX212) causing the mounted mirror to oscillate back and forth. Channel 2 of the pen recorder checks the timing accuracy of the triangular wave of the function generator (3310A Function Generator Hewlett Packard) used for controlling the frequency of the pen motor.

Because increasing the drive to achieve a greater angular rotation damages the pen motor, the motor is designed to rotate about $\pm$ 15^0. To vary sweep length on the projection screen the rotating mirror is moved towards or away from the projection screen: the distance was arranged to give a sweep length which resulted in 45^0 neck rotation, as well as 45^0 flexion and extension, from the neutral position of the neck. The light source could be adjusted to sweep horizontally, vertically and obliquely on the projection screen.

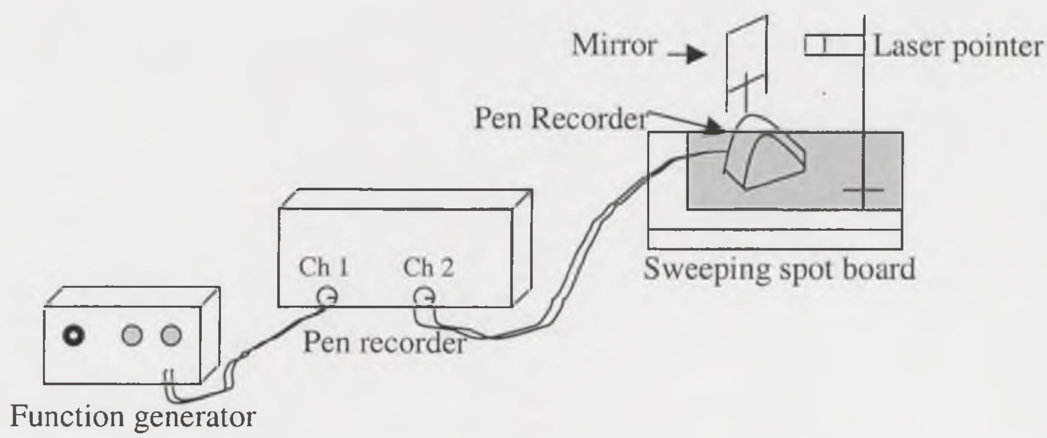


Figure A3.1 The sweeping spot board connected to the pen recorder and function generator.

Appendix 4: The difference between loudspeakers and headphones as sound source.

Introduction

In experiments 3 and 4 the two frequencies, 1595Hz and 2916Hz, were chosen from a previous study (Sakellari and Soames 1996) which used loudspeakers as the sound source. Due to the problems associated with loudspeakers in the laboratory, headphones as the sound source were considered. Thus, the aim of this study was to examine whether there was any difference between using loudspeakers and headphones as the sound source.

Materials and methods

Five healthy subjects (4 females 1 males), aged between 22 and 37 years, agreed to participate in the experiment: they did not participate in subsequent experiments. Subject's eye level above the ground, taken on the left side and measured to the left lateral canthus, and left foot length were measured for achieving 45^0 neck flexion/extension (details are given in Figure 3.3 page 36).

A total of 20 measurements, each of 20s duration, (looking ahead, 45^0 neck flexion/extension and 45^0 neck rotation to the right and left, each with loudspeakers (Goodman M500) and headphones (JVC HA-D570B) using frequencies 1595Hz and 2916Hz at 80dB were taken from each subject. The loudspeakers were placed at ear height 40 cm from each ear.

After informing subjects of the nature of the experiment and explaining what was required, they stood comfortably erect barefoot, arms hanging loosely at the sides and feet together on the force platform. Subjects were instructed to focus on the marker on the screen in front of them (Figure A4.1), the recording of postural sway behaviour was then taken.

The standard postural sway behaviour parameters (details are given in Chapter 3 part 3.3) were calculated from the individual recordings. Three-way analyses of variance was conducted for each sway parameter with head position, sound source and frequency as independent variables, with t-tests being conducted if significant differences were observed in the three-way analyses. The 5% level of significance was used unless otherwise stated.

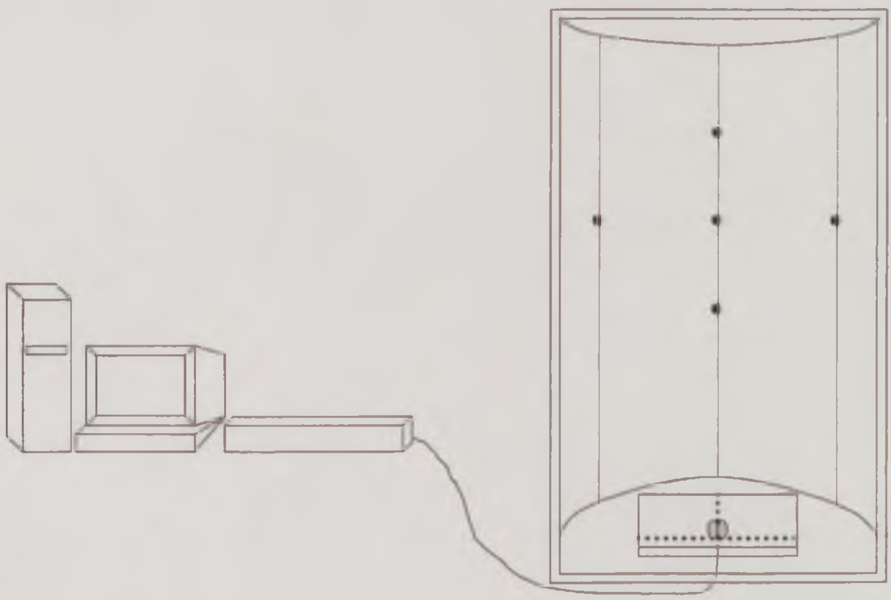


Figure A4.1 Five-marker position on the screen for achieving neck looking directly ahead, 45^0 neck flexion/extension and 45^0 neck rotation to the right and left.

Results

Neck position

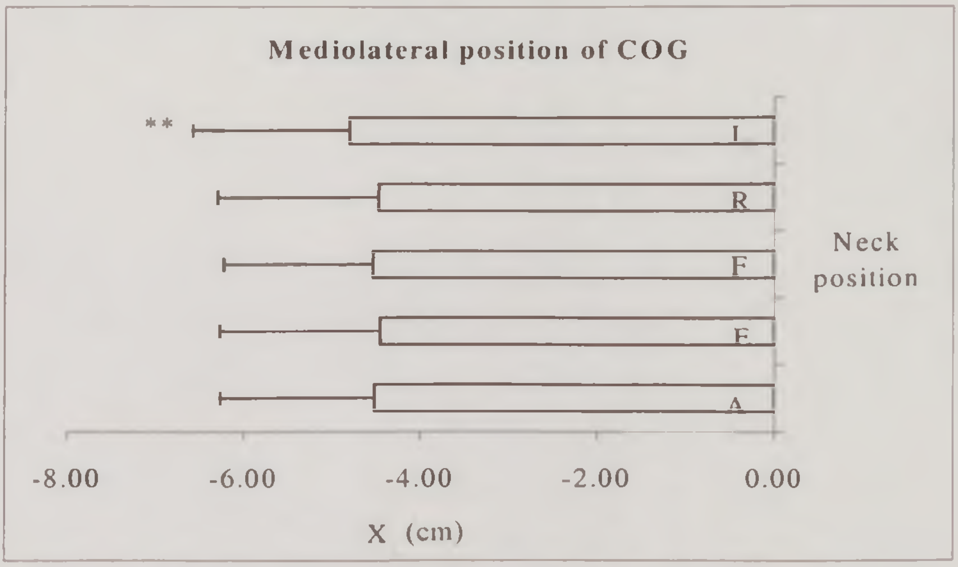
Three-way analyses of variance (Table A4.1) showed a significant ($p<0.01$) neck position effect on X and Y. As shown in Figure A4.2 with the neck rotated to the left there was a significant ($p<0.01$) shift of the COG projection to the left compared with other neck positions.

However, as shown in Figure A4.2 looking directly ahead as well as neck extension resulted in a significant ($p<0.01$) shift of the COG posteriorly compared with other neck positions.

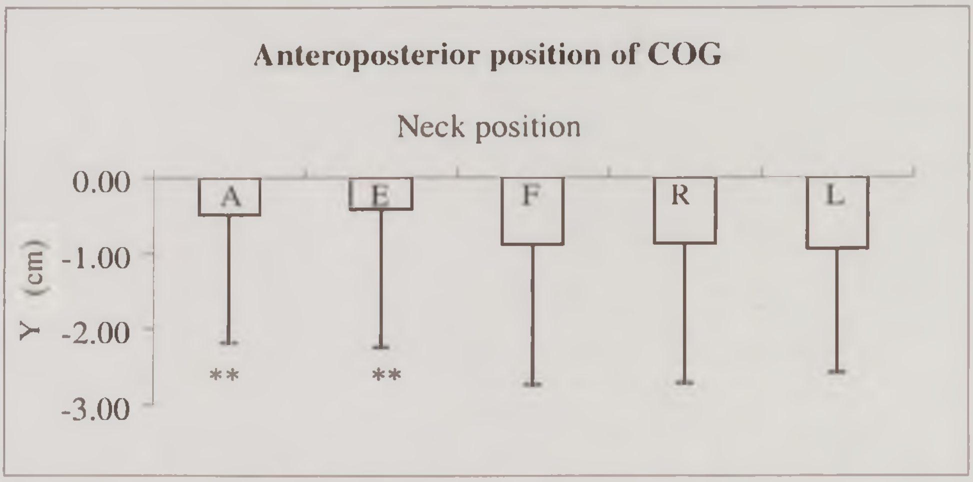
Postural sway parameter	Neck position (Np)	Sound source (Ss)	Sound frequency (Sf)	Np * Ss	Np*Sf	Ss*Sf	Npt*Ss*Sf
X	$F_{4,16} = 4.89$ **	$F_{1,4} = 3.77$	$F_{1,4} = 0.05$	$F_{4,16} = 1.53$	$F_{4,16} = 1.59$	$F_{1,4} = 0.02$	$F_{4,16} = 0.72$
Y	$F_{4,16} = 13.46$ **	$F_{1,4} = 8.06$ *	$F_{1,4} = 0.00$	$F_{4,16} = 3.84$ *	$F_{4,16} = 1.77$	$F_{1,4} = 0.70$	$F_{4,16} = 4.72$ *
Sx	$F_{4,16} = 2.29$	$F_{1,4} = 2.79$	$F_{1,4} = 8.32$ *	$F_{4,16} = 2.91$	$F_{4,16} = 1.03$	$F_{1,4} = 0.87$	$F_{4,16} = 0.11$
Sr	$F_{4,16} = 1.91$	$F_{1,4} = 1.51$	$F_{1,4} = 7.38$	$F_{4,16} = 3.99$ *	$F_{4,16} = 0.97$	$F_{1,4} = 1.01$	$F_{4,16} = 0.23$
Sl	$F_{4,16} = 2.19$	$F_{1,4} = 4.70$	$F_{1,4} = 7.07$	$F_{4,16} = 1.49$	$F_{4,16} = 1.07$	$F_{1,4} = 0.56$	$F_{4,16} = 0.20$
Sy	$F_{4,16} = 2.38$	$F_{1,4} = 1.89$	$F_{1,4} = 2.45$	$F_{4,16} = 2.14$	$F_{4,16} = 0.92$	$F_{1,4} = 2.19$	$F_{4,16} = 0.06$
Sa	$F_{4,16} = 1.64$	$F_{1,4} = 0.64$	$F_{1,4} = 2.05$	$F_{4,16} = 2.21$	$F_{4,16} = 1.23$	$F_{1,4} = 1.95$	$F_{4,16} = 0.78$
Sp	$F_{4,16} = 2.71$	$F_{1,4} = 3.30$	$F_{1,4} = 2.56$	$F_{4,16} = 1.31$	$F_{4,16} = 0.53$	$F_{1,4} = 0.81$	$F_{4,16} = 0.20$
TLx	$F_{4,16} = 0.87$	$F_{1,4} = 1.95$	$F_{1,4} = 4.64$	$F_{4,16} = 1.85$	$F_{4,16} = 0.38$	$F_{1,4} = 0.00$	$F_{4,16} = 0.43$
TLy	$F_{4,16} = 1.64$	$F_{1,4} = 2.61$	$F_{1,4} = 3.57$	$F_{4,16} = 1.60$	$F_{4,16} = 0.41$	$F_{1,4} = 0.49$	$F_{4,16} = 0.51$
TL	$F_{4,16} = 1.10$	$F_{1,4} = 2.65$	$F_{1,4} = 4.35$	$F_{4,16} = 1.76$	$F_{4,16} = 0.40$	$F_{1,4} = 0.15$	$F_{4,16} = 0.27$
Vxm	$F_{4,16} = 0.87$	$F_{1,4} = 1.95$	$F_{1,4} = 4.64$	$F_{4,16} = 1.85$	$F_{4,16} = 0.38$	$F_{1,4} = 0.00$	$F_{4,16} = 0.43$
Vym	$F_{4,16} = 1.64$	$F_{1,4} = 2.61$	$F_{1,4} = 3.57$	$F_{4,16} = 1.60$	$F_{4,16} = 0.41$	$F_{1,4} = 0.49$	$F_{4,16} = 0.54$
Vm	$F_{4,16} = 1.10$	$F_{1,4} = 2.65$	$F_{1,4} = 4.35$	$F_{4,16} = 1.76$	$F_{4,16} = 0.40$	$F_{1,4} = 0.15$	$F_{4,16} = 0.27$
Ay	$F_{4,16} = 2.42$	$F_{1,4} = 3.77$	$F_{1,4} = 0.20$	$F_{4,16} = 0.60$	$F_{4,16} = 0.42$	$F_{1,4} = 0.00$	$F_{4,16} = 0.17$

* $p<0.05$, ** $p<0.01$ significant influence on each postural sway parameter.

Table A4.1 The influence of the main variables and their interaction on postural sway behaviour parameters.



** significantly (p<0.01) greater from all other neck position.

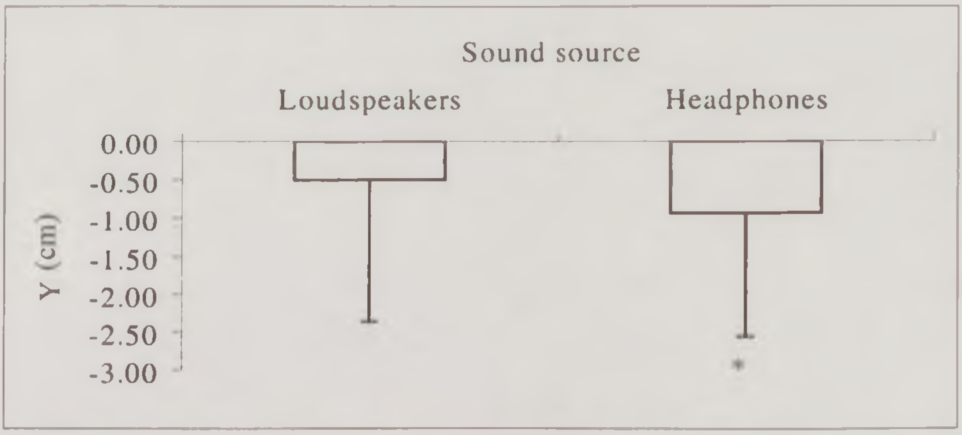


** significantly (p<0.01) less than all other neck position.

Figure A4.2 **The influence of neck position (A = looking directly ahead, E = extension, F = flexion, R = right, L = left) on the centre of gravity projection in mediolateral (X) and anteroposterior (Y) directions.**

Sound source

Three-way analyses of variance (Table A4.1) showed that the sound source only had a significant effect on the anteroposterior COG projection, with the headphones causing a posterior shift compared with the loudspeakers (Figure. A4.3).

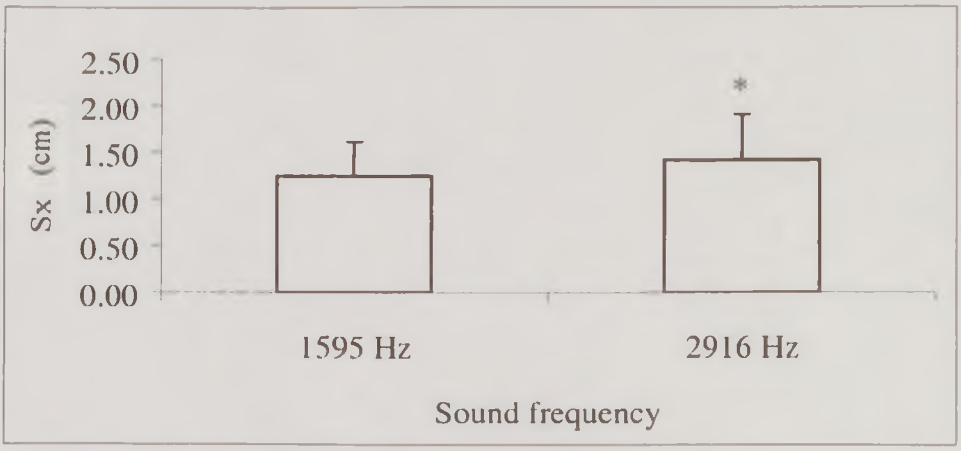


* significantly (p<0.05) less from loudspeakers.

Figure A4.3 The influence of the sound source on the anteroposterior centre of gravity projection (Y).

Sound frequency

Three-way analyses of variance (Table A4.1) also showed that the frequency of the sound significantly influenced the mean magnitude of mediolateral sway, with the frequency 2916Hz eliciting greater sway magnitude than did 1595Hz (Figure A4.4).

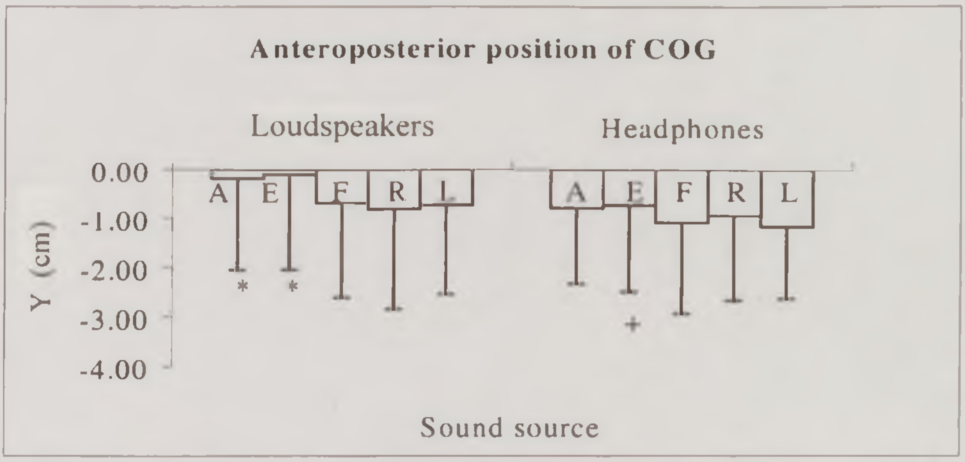


* significantly (p<0.05) greater from 1595Hz.

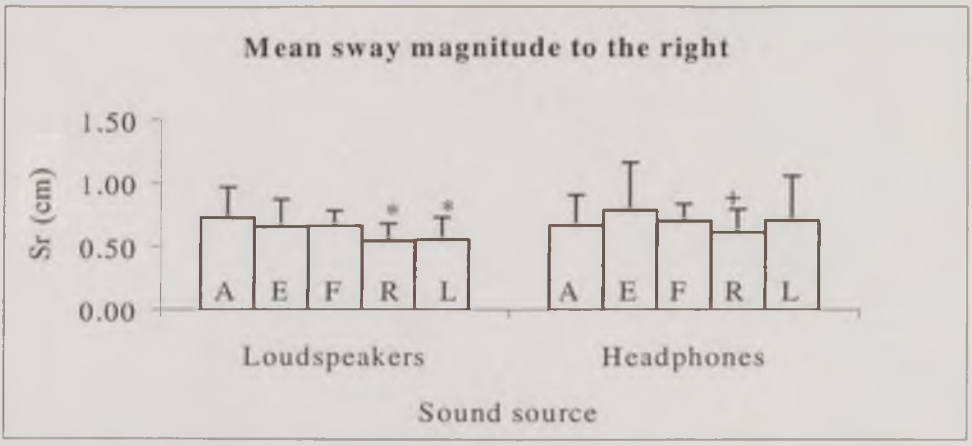
Figure A4.4 The influence of sound frequency on the magnitude of mediolateral sway (Sx).

Interaction between neck position and sound source

A significant neck position and sound source interaction was also observed for Y and Sr (Table A4.1). As shown in Figure A4.5 both looking directly ahead and neck extension significantly reduced the posterior projection of the COG than did the remaining neck postures.



* significantly (p<0.05) less from F, R and L.



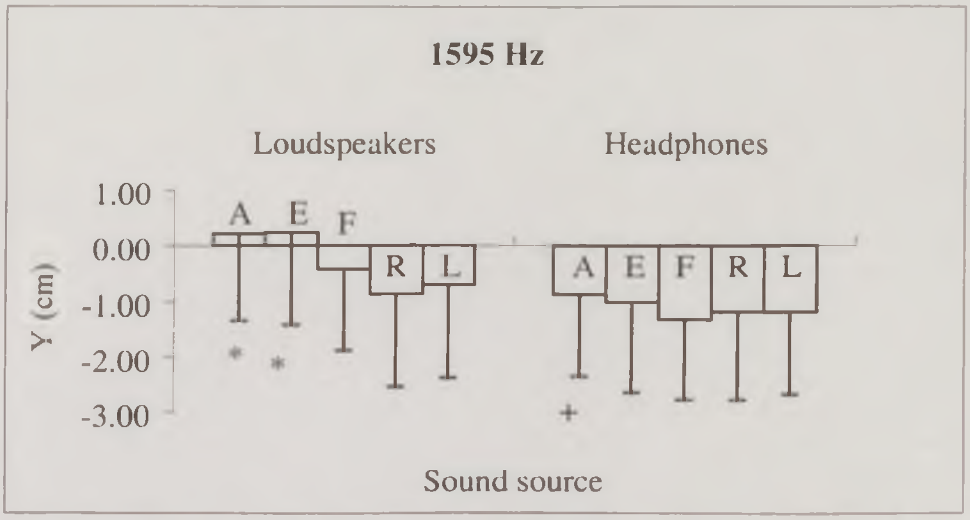
\+ significantly (p<0.05) less from R and L.
* R significantly (p<0.05) less from A and F.
* L significantly (p<0.05) less from A, E and F.
\+ significantly (p<0.05) less from E and F.

Figure A4.5 **The interaction between neck position (A = looking directly ahead, E = extension, F = flexion, R = right, L = left) and sound source (loudspeakers and headphones) on the anteroposterior centre of gravity projection (Y) and the magnitude of sway to the right (Sr).**

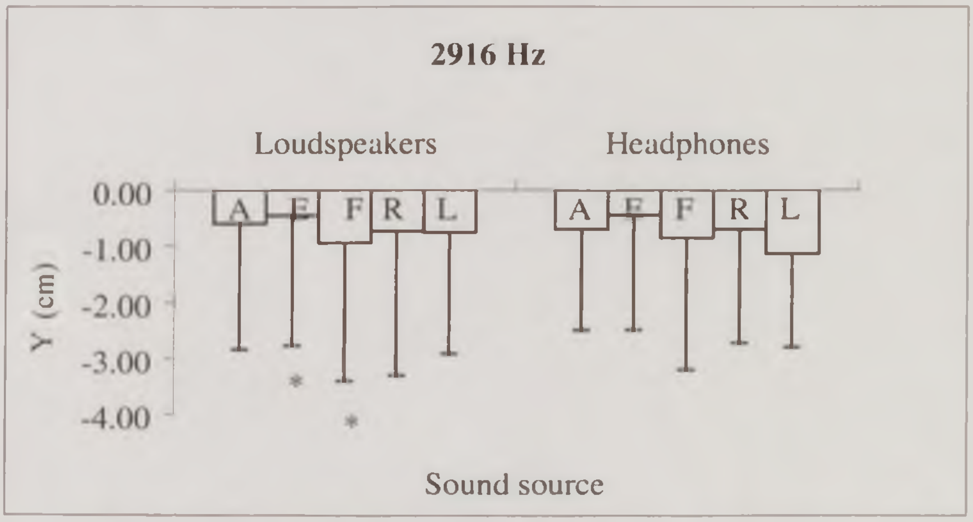
However, with the headphones (Figure A4.5) only neck extension had a significant effect on the anteroposterior position of the COG projection. There was a significantly smaller mean sway to the right and left with the loudspeakers compared with looking directly ahead or with neck flexion. In addition, with rotation to the left there was a significantly reduced sway to the right compared with neck extension. With headphones there was a significantly reduced sway to the right compared with neck extension or neck flexion.

Interaction between neck position, sound source and sound frequency

Three–way analyses of variance (Table A4.1) also showed a significant interaction between neck position, sound source and sound frequency for the anteroposterior position of the COG projection. As shown in Figure A4.6 at 1595Hz with loudspeakers the COG was shifted anteriorly when looking directly ahead as well as with extension compared with all other neck positions. However, with headphones when looking directly ahead the COG moved anteriorly compared with rotation to the right. In contrast, at 2916Hz only the loudspeakers showed a significant interaction, such that with neck extension the COG was shifted anteriorly compared with looking directly ahead, neck flexion or rotation to the left. In addition, with neck flexion the COG moved posteriorly compared with rotation to the right.



* significantly (p<0.05) greater from F, R and L.
+ significantly (p<0.05) greater from R.



* E significantly (p<0.05) greater from A, F and L.
* F significantly (p<0.05) less from R.

Figure A4.6 The interaction between neck position (A = looking directly ahead, E = extension, F = flexion, R = right, L = left), sound source (loudspeakers and headphones) and sound frequency (1595Hz and 2916Hz) on the anteroposterior centre of gravity projection (Y).

Discussion

The different sound sources, loudspeakers and headphones, only had different effects on the projection of COG in the anteroposterior direction.

Although some differences, as seen in the interaction between neck position and sound source for Y and Sr (Figure A4.5) as well as between neck position, sound source and sound frequency for Y (Figure A4.6), were observed with headphones, unlike the loudspeakers there were no differences influenced by neck position. It is possible that with loudspeakers the intensity of sound changes during body sway depending on the direction and magnitude of movement. Moreover, with loudspeakers the intensity of sound transmitted to each ear may change due to neck rotation when the ears are not directly in line with the emitted sound source. Headphones, therefore seems to have the advantage that the sound is always consistently direct to the ear, irrespective of body sway or changes in neck position.

Even though the sound frequency has previously been reported to influence the regulation of the anteroposterior sway (Sakellari and Soames 1996), this effect was not observed in this study. However, the frequency of sound was observed to influence sway in the mediolateral direction, with 2916Hz promoting stability more than 1595Hz, thus confirming the observation of Sakellari and Soames (1996).

Conclusion

Headphones appear to be a more appropriate choice than loudspeakers when these are changes in neck position. The effect of the frequency of sound is that subjects were more stable at 1595Hz than at 2916Hz.

Appendix 5: Analyses of variance for Chapter 4: Experiment 1.

Postural Sway Parameter	Sex	Vision	Sex * Vision	Neck Rotation	Sex * Neck Rotation	Neck Flexion/ Extension (Neck F/E)	Sex * Neck F/E
X	$F_{1,56} = 0.00$	$F_{1,56} = 5.42$ *	$F_{1,56} = 1.73$	$F_{2,112} = 2.86$	$F_{2,112} = 0.50$	$F_{2,112} = 2.40$	$F_{2,112} = 0.43$
Y	$F_{1,56} = 1.51$	$F_{1,56} = 51.12$ **	$F_{1,56} = 1.46$	$F_{2,112} = 5.37$ **	$F_{2,112} = 0.01$	$F_{2,112} = 23.72$ **	$F_{2,112} = 3.09$
Sx	$F_{1,56} = 0.18$	$F_{1,56} = 191.06$ **	$F_{1,56} = 0.01$	$F_{2,112} = 4.60$ *	$F_{2,112} = 0.91$	$F_{2,112} = 6.42$ **	$F_{2,112} = 0.12$
Sr	$F_{1,56} = 0.15$	$F_{1,56} = 195.97$ **	$F_{1,56} = 0.04$	$F_{2,112} = 4.29$ *	$F_{2,112} = 0.50$	$F_{2,112} = 7.49$ **	$F_{2,112} = 0.32$
Sl	$F_{1,56} = 0.28$	$F_{1,56} = 183.48$ **	$F_{1,56} = 0.01$	$F_{2,112} = 3.00$	$F_{2,112} = 1.61$	$F_{2,112} = 4.96$ **	$F_{2,112} = 0.05$
Sy	$F_{1,56} = 0.02$	$F_{1,56} = 153.87$ **	$F_{1,56} = 0.34$	$F_{2,112} = 3.31$ *	$F_{2,112} = 0.07$	$F_{2,112} = 19.42$ **	$F_{2,112} = 0.40$
Sa	$F_{1,56} = 0.04$	$F_{1,56} = 151.81$ **	$F_{1,56} = 0.15$	$F_{2,112} = 3.82$ *	$F_{2,112} = 0.04$	$F_{2,112} = 18.09$ **	$F_{2,112} = 0.39$
Sp	$F_{1,56} = 0.01$	$F_{1,56} = 151.01$ **	$F_{1,56} = 0.30$	$F_{2,112} = 1.75$	$F_{2,112} = 0.01$	$F_{2,112} = 20.29$ **	$F_{2,112} = 0.04$
TL	$F_{1,56} = 4.40$ *	$F_{1,56} = 90.88$ **	$F_{1,56} = 0.33$	$F_{2,112} = 0.14$	$F_{2,112} = 0.08$	$F_{2,112} = 7.35$ **	$F_{2,112} = 0.39$
TLx	$F_{1,56} = 5.18$ *	$F_{1,56} = 105.97$ **	$F_{1,56} = 0.04$	$F_{2,112} = 0.46$	$F_{2,112} = 0.22$	$F_{2,112} = 5.76$ **	$F_{2,112} = 1.06$
TLy	$F_{1,56} = 2.39$	$F_{1,56} = 76.28$ **	$F_{1,56} = 0.84$	$F_{2,112} = 0.07$	$F_{2,112} = 0.63$	$F_{2,112} = 7.09$ **	$F_{2,112} = 0.07$
Vm	$F_{1,56} = 4.40$ *	$F_{1,56} = 90.88$ **	$F_{1,56} = 0.33$	$F_{2,112} = 0.14$	$F_{2,112} = 0.08$	$F_{2,112} = 7.35$ **	$F_{2,112} = 0.39$
Vxm	$F_{1,56} = 5.18$ *	$F_{1,56} = 105.97$ **	$F_{1,56} = 0.04$	$F_{2,112} = 0.46$	$F_{2,112} = 0.22$	$F_{2,112} = 5.76$ **	$F_{2,112} = 1.06$
Vym	$F_{1,56} = 2.45$	$F_{1,56} = 78.55$ **	$F_{1,56} = 1.01$	$F_{2,112} = 0.05$	$F_{2,112} = 0.46$	$F_{2,112} = 7.21$ **	$F_{2,112} = 0.19$
Ay	$F_{1,56} = 1.36$	$F_{1,56} = 1.33$	$F_{1,56} = 1.75$	$F_{2,112} = 4.45$ *	$F_{2,112} = 1.08$	$F_{2,112} = 0.75$	$F_{2,112} = 1.05$

Postural Sway Parameter	Vision * Neck Rotation	Sex * Vision * Neck Rotation	Vision * Neck F/E	Sex * Vision * Neck F/E	Neck Rotation * Neck F/E	Sex * Neck Rotation * Neck F/E	Vision * Neck Rotation * Neck F/E	Sex * Vision * Neck Rotation * Neck F/E
X	$F_{2,112} = 0.13$	$F_{2,112} = 1.34$	$F_{2,112} = 0.82$	$F_{2,112} = 5.47$ **	$F_{4,224} = 0.19$	$F_{4,224} = 0.34$	$F_{4,224} = 1.08$	$F_{4,224} = 0.61$
Y	$F_{2,112} = 4.14$ *	$F_{2,112} = 0.04$	$F_{2,112} = 3.91$ *	$F_{2,112} = 0.13$	$F_{4,224} = 7.30$ **	$F_{4,224} = 4.21$ **	$F_{4,224} = 0.54$	$F_{4,224} = 0.46$
Sx	$F_{2,112} = 9.25$ **	$F_{2,112} = 1.25$	$F_{2,112} = 5.82$ **	$F_{2,112} = 4.51$ *	$F_{4,224} = 0.47$	$F_{4,224} = 1.27$	$F_{4,224} = 0.65$	$F_{4,224} = 0.08$
Sr	$F_{2,112} = 12.64$ **	$F_{2,112} = 1.01$	$F_{2,112} = 5.59$ **	$F_{2,112} = 3.64$ *	$F_{4,224} = 0.45$	$F_{4,224} = 1.74$	$F_{4,224} = 0.64$	$F_{4,224} = 0.31$
Sl	$F_{2,112} = 5.65$ **	$F_{2,112} = 0.82$	$F_{2,112} = 5.28$ **	$F_{2,112} = 3.60$ *	$F_{4,224} = 1.12$	$F_{4,224} = 1.20$	$F_{4,224} = 0.53$	$F_{4,224} = 0.07$
Sy	$F_{2,112} = 5.04$ **	$F_{2,112} = 0.52$	$F_{2,112} = 19.48$ **	$F_{2,112} = 1.54$	$F_{4,224} = 2.49$ *	$F_{4,224} = 0.83$	$F_{4,224} = 2.00$	$F_{4,224} = 0.19$
Sa	$F_{2,112} = 4.44$ *	$F_{2,112} = 0.58$	$F_{2,112} = 23.04$ **	$F_{2,112} = 0.66$	$F_{4,224} = 2.48$ *	$F_{4,224} = 1.50$	$F_{4,224} = 2.16$	$F_{4,224} = 0.36$
Sp	$F_{2,112} = 4.41$ *	$F_{2,112} = 0.36$	$F_{2,112} = 15.81$ **	$F_{2,112} = 1.67$	$F_{4,224} = 3.52$ **	$F_{4,224} = 0.52$	$F_{4,224} = 2.43$ *	$F_{4,224} = 0.48$
TL	$F_{2,112} = 9.18$ **	$F_{2,112} = 0.77$	$F_{2,112} = 8.60$ **	$F_{2,112} = 0.97$	$F_{4,224} = 2.21$	$F_{4,224} = 0.92$	$F_{4,224} = 2.62$ *	$F_{4,224} = 0.17$
TLx	$F_{2,112} = 13.20$ **	$F_{2,112} = 1.82$	$F_{2,112} = 6.98$ **	$F_{2,112} = 2.20$	$F_{4,224} = 0.55$	$F_{4,224} = 0.47$	$F_{4,224} = 2.15$	$F_{4,224} = 0.30$
TLy	$F_{2,112} = 4.72$ *	$F_{2,112} = 0.17$	$F_{2,112} = 9.12$ **	$F_{2,112} = 0.29$	$F_{4,224} = 5.06$ **	$F_{4,224} = 1.87$	$F_{4,224} = 2.78$ *	$F_{4,224} = 0.17$
Vm	$F_{2,112} = 9.18$ **	$F_{2,112} = 0.77$	$F_{2,112} = 8.60$ **	$F_{2,112} = 0.97$	$F_{4,224} = 2.21$	$F_{4,224} = 0.92$	$F_{4,224} = 2.62$ *	$F_{4,224} = 0.17$
Vxm	$F_{2,112} = 13.20$ **	$F_{2,112} = 1.82$	$F_{2,112} = 6.98$ **	$F_{2,112} = 2.20$	$F_{4,224} = 0.55$	$F_{4,224} = 0.47$	$F_{4,224} = 2.15$	$F_{4,224} = 0.30$
Vym	$F_{2,112} = 5.47$ **	$F_{2,112} = 0.23$	$F_{2,112} = 7.21$ **	$F_{2,112} = 0.07$	$F_{4,224} = 4.34$ **	$F_{4,224} = 1.42$	$F_{4,224} = 2.34$	$F_{4,224} = 0.20$
Ay	$F_{2,112} = 0.25$	$F_{2,112} = 0.10$	$F_{2,112} = 0.17$	$F_{2,112} = 1.24$	$F_{4,224} = 0.46$	$F_{4,224} = 0.45$	$F_{4,224} = 1.00$	$F_{4,224} = 0.59$

* $p<0.05$, ** $p<0.01$ significant influence on each variable or combination of variables on each postural sway parameter.

Table A5.1 The influence of sex, vision, neck rotation and neck flexion/extension and their interactions on the various parameters of postural sway behaviour.

Appendix 6: Analyses of variance for Chapter 5: Experiment 2.

Postural Sway Parameter	Sex	Velocity of Head Movement (Velocity)	Sex * Velocity	Direction of Head Movement (Direction)	Sex * Direction	Velocity * Direction	Sex * Velocity * Direction
X	$F_{1,28} = 13.81$ **	$F_{1,28} = 0.10$	$F_{1,28} = 1.31$	$F_{7,196} = 0.58$	$F_{7,196} = 0.98$	$F_{7,196} = 0.65$	$F_{7,196} = 0.56$
Y	$F_{1,28} = 5.65$ *	$F_{1,28} = 0.00$	$F_{1,28} = 4.39$ *	$F_{7,196} = 3.65$ **	$F_{7,196} = 0.54$	$F_{7,196} = 0.61$	$F_{7,196} = 0.25$
Sx	$F_{1,28} = 0.00$	$F_{1,28} = 38.30$ **	$F_{1,28} = 0.03$	$F_{7,196} = 5.22$ **	$F_{7,196} = 0.79$	$F_{7,196} = 1.58$	$F_{7,196} = 0.42$
Sr	$F_{1,28} = 0.00$	$F_{1,28} = 42.42$ **	F1,28 = 0.05	$F_{7,196} = 4.68$ **	$F_{7,196} = 0.63$	$F_{7,196} = 1.59$	$F_{7,196} = 0.29$
Sl	$F_{1,28} = 0.02$	$F_{1,28} = 32.68$ **	$F_{1,28} = 0.01$	$F_{7,196} = 4.73$ **	$F_{7,196} = 0.94$	$F_{7,196} = 1.47$	$F_{7,196} = 0.54$
Sy	$F_{1,28} = 0.18$	$F_{1,28} = 97.80$ **	$F_{1,28} = 0.00$	$F_{7,196} = 8.88$ **	$F_{7,196} = 1.01$	$F_{7,196} = 4.48$ **	$F_{7,196} = 0.89$
Sa	$F_{1,28} = 0.20$	$F_{1,28} = 85.41$ **	$F_{1,28} = 0.01$	$F_{7,196} = 5.37$ **	$F_{7,196} = 0.83$	$F_{7,196} = 3.18$ **	$F_{7,196} = 1.17$
Sμ	$F_{1,28} = 0.16$	$F_{1,28} = 89.80$ **	$F_{1,28} = 0.00$	$F_{7,196} = 9.62$ **	$F_{7,196} = 0.95$	$F_{7,196} = 3.90$ **	$F_{7,196} = 0.97$
TL	$F_{1,28} = 0.10$	$F_{1,28} = 55.76$ **	$F_{1,28} = 0.26$	$F_{7,196} = 7.05$ **	$F_{7,196} = 0.94$	$F_{7,196} = 1.75$	$F_{7,196} = 0.64$
TLx	$F_{1,28} = 0.08$	$F_{1,28} = 42.90$ **	$F_{1,28} = 0.47$	$F_{7,196} = 7.82$ **	$F_{7,196} = 0.57$	$F_{7,196} = 1.99$	$F_{7,196} = 0.58$
TLy	$F_{1,28} = 0.17$	$F_{1,28} = 56.34$ **	$F_{1,28} = 0.02$	$F_{7,196} = 7.71$ **	$F_{7,196} = 1.57$	$F_{7,196} = 3.03$ **	$F_{7,196} = 0.90$
Vm	$F_{1,28} = 0.10$	$F_{1,28} = 55.76$ **	$F_{1,28} = 0.26$	$F_{7,196} = 7.05$ **	$F_{7,196} = 0.94$	$F_{7,196} = 1.75$	$F_{7,196} = 0.64$
Vxm	$F_{1,28} = 0.08$	$F_{1,28} = 42.90$ **	$F_{1,28} = 0.47$	$F_{7,196} = 7.82$ **	$F_{7,196} = 0.57$	$F_{7,196} = 1.99$	$F_{7,196} = 0.58$
Vym	$F_{1,28} = 0.17$	$F_{1,28} = 56.34$ **	$F_{1,28} = 0.02$	$F_{7,196} = 7.71$ **	$F_{7,196} = 1.57$	$F_{7,196} = 3.03$ **	$F_{7,196} = 0.90$
Ay	$F_{1,28} = 4.12$	$F_{1,28} = 0.17$	$F_{1,28} = 3.41$	$F_{7,196} = 0.67$	$F_{7,196} = 1.17$	$F_{7,196} = 0.81$	$F_{7,196} = 1.46$

* $p<0.05$, ** $p<0.01$ significant influence on each variable or combination of variables on each postural sway parameter.

Table A6.1 The influence of sex, velocity and direction of head movement and their interactions on the various parameters of postural sway behaviour.

Appendix 7: Analyses of variance for Chapter 6.

Postural Sway Parameter	Sex	Condition of Head (Condition)	Sex * Condition	Direction of Head Movement (Direction)	Sex * Direction	Condition * Direction	Sex * Condition * Direction
X	$F_{1,14} = 5.10$ *	$F_{2,28} = 3.50$ *	$F_{2,28} = 0.03$	$F_{7,98} = 1.33$	$F_{7,98} = 1.15$	$F_{14,196} = 1.01$	$F_{14,196} = 1.89$ *
Y	$F_{1,14} = 1.21$	$F_{2,28} = 2.91$	$F_{2,28} = 0.23$	$F_{7,98} = 5.92$ **	$F_{7,98} = 1.02$	$F_{14,196} = 2.67$ **	$F_{14,196} = 1.23$
Sx	$F_{1,14} = 0.37$	$F_{2,28} = 64.09$ **	$F_{2,28} = 0.44$	$F_{7,98} = 3.56$ **	$F_{7,98} = 0.68$	$F_{14,196} = 2.02$ *	$F_{14,196} = 0.64$
Sr	$F_{1,14} = 0.48$	$F_{2,28} = 66.89$ **	$F_{2,28} = 0.41$	$F_{7,98} = 3.70$ **	$F_{7,98} = 0.91$	$F_{14,196} = 2.19$ **	$F_{14,196} = 0.67$
Sl	$F_{1,14} = 0.50$	$F_{2,28} = 59.44$ **	$F_{2,28} = 0.45$	$F_{7,98} = 2.84$ **	$F_{7,98} = 0.56$	$F_{14,196} = 1.65$	$F_{14,196} = 0.59$
Sy	$F_{1,14} = 0.43$	$F_{2,28} = 155.32$ **	$F_{2,28} = 0.63$	$F_{7,98} = 5.67$ **	$F_{7,98} = 0.55$	$F_{14,196} = 3.74$ **	$F_{14,196} = 0.87$
Sa	$F_{1,14} = 0.49$	$F_{2,28} = 145.15$ **	$F_{2,28} = 0.44$	$F_{7,98} = 4.73$ **	$F_{7,98} = 0.90$	$F_{14,196} = 3.24$ **	$F_{14,196} = 0.90$
Sp	$F_{1,14} = 0.34$	$F_{2,28} = 149.97$ **	$F_{2,28} = 0.80$	$F_{7,98} = 5.36$ **	$F_{7,98} = 0.48$	$F_{14,196} = 3.00$ **	$F_{14,196} = 0.64$
TL	$F_{1,14} = 0.01$	$F_{2,28} = 35.32$ **	$F_{2,28} = 0.76$	$F_{7,98} = 4.69$ **	$F_{7,98} = 0.74$	$F_{14,196} = 1.83$ *	$F_{14,196} = 0.86$
TLx	$F_{1,14} = 0.00$	$F_{2,28} = 30.48$ **	$F_{2,28} = 0.54$	$F_{7,98} = 5.33$ **	$F_{7,98} = 0.46$	$F_{14,196} = 2.27$ **	$F_{14,196} = 0.70$
TLy	$F_{1,14} = 0.04$	$F_{2,28} = 37.70$ **	$F_{2,28} = 0.12$	$F_{7,98} = 4.73$ **	$F_{7,98} = 1.11$	$F_{14,196} = 2.12$ *	$F_{14,196} = 1.10$
Vm	$F_{1,14} = 0.03$	$F_{2,28} = 140.63$ **	$F_{2,28} = 0.08$	$F_{7,98} = 4.71$ **	$F_{7,98} = 0.85$	$F_{14,196} = 1.83$ *	$F_{14,196} = 0.80$
Vxm	$F_{1,14} = 0.06$	$F_{2,28} = 106.52$ **	$F_{2,28} = 0.08$	$F_{7,98} = 5.16$ **	$F_{7,98} = 0.52$	$F_{14,196} = 2.35$ **	$F_{14,196} = 0.67$
Vym	$F_{1,14} = 0.02$	$F_{2,28} = 163.35$ **	$F_{2,28} = 0.25$	$F_{7,98} = 4.70$ **	$F_{7,98} = 1.25$	$F_{14,196} = 2.16$ *	$F_{14,196} = 1.01$
Ay	$F_{1,14} = 0.02$	$F_{2,28} = 2.41$	$F_{2,28} = 0.07$	$F_{7,98} = 0.84$	$F_{7,98} = 1.67$	$F_{14,196} = 0.46$	$F_{14,196} = 0.92$

* $p<0.05$, ** $p<0.01$ significant influence on each variable or combination of variables on each postural sway parameter.

Table A7.1 **The influence of sex, the condition of head (static/dynamic) and the direction of head movement and their interactions on the various parameters of postural sway behaviour.**

Appendix 8: Analyses of variance for Chapter 7: Experiment 3.

Postural Sway Parameter	Sex	Vision	Sex * Vision	Sound	Sex * Sound	Neck Rotation	Sex * Neck Rotation	Neck Flexion/ Extension (Neck F/E)	Sex * Neck F/E
X	$F_{1,28} = 3.83$	$F_{1,28} = 9.69$ **	$F_{1,28} = 1.36$	$F_{1,28} = 0.26$	$F_{1,28} = 0.00$	$F_{2,56} = 8.49$ **	$F_{2,56} = 0.04$	$F_{2,56} = 0.43$	$F_{2,56} = 1.03$
Y	$F_{1,28} = 0.01$	$F_{1,28} = 0.01$	$F_{1,28} = 2.37$	$F_{1,28} = 1.30$	$F_{1,28} = 0.60$	$F_{2,56} = 0.63$	$F_{2,56} = 1.63$	$F_{2,56} = 2.27$	$F_{2,56} = 1.15$
Sx	$F_{1,28} = 0.34$	$F_{1,28} = 69.89$ **	$F_{1,28} = 2.55$	$F_{1,28} = 5.51$ *	$F_{1,28} = 1.89$	$F_{2,56} = 2.19$	$F_{2,56} = 0.68$	$F_{2,56} = 7.08$ **	$F_{2,56} = 0.17$
Sr	$F_{1,28} = 0.15$	$F_{1,28} = 57.67$ **	$F_{1,28} = 1.66$	$F_{1,28} = 4.72$ *	$F_{1,28} = 1.85$	$F_{2,56} = 1.48$	$F_{2,56} = 1.09$	$F_{2,56} = 7.25$ **	$F_{2,56} = 0.91$
Sl	$F_{1,28} = 0.62$	$F_{1,28} = 72.48$ **	$F_{1,28} = 3.24$	$F_{1,28} = 6.08$ *	$F_{1,28} = 1.85$	$F_{2,56} = 2.25$	$F_{2,56} = 0.82$	$F_{2,56} = 4.48$ *	$F_{2,56} = 0.04$
Sy	$F_{1,28} = 0.19$	$F_{1,28} = 65.82$ **	$F_{1,28} = 1.42$	$F_{1,28} = 1.68$	$F_{1,28} = 2.34$	$F_{2,56} = 0.64$	$F_{2,56} = 1.77$	$F_{2,56} = 12.53$ **	$F_{2,56} = 1.22$
Sa	$F_{1,28} = 0.08$	$F_{1,28} = 79.85$ **	$F_{1,28} = 1.22$	$F_{1,28} = 2.47$	$F_{1,28} = 2.27$	$F_{2,56} = 0.94$	$F_{2,56} = 1.06$	$F_{2,56} = 9.46$ **	$F_{2,56} = 0.36$
Sp	$F_{1,28} = 0.40$	$F_{1,28} = 52.31$ **	$F_{1,28} = 1.78$	$F_{1,28} = 1.27$	$F_{1,28} = 2.69$	$F_{2,56} = 0.08$	$F_{2,56} = 2.87$	$F_{2,56} = 13.03$ **	$F_{2,56} = 2.68$
TL	$F_{1,28} = 0.77$	$F_{1,28} = 35.16$ **	$F_{1,28} = 7.03$ *	$F_{1,28} = 2.65$	$F_{1,28} = 4.24$ *	$F_{2,56} = 2.26$	$F_{2,56} = 0.01$	$F_{2,56} = 8.49$ *	$F_{2,56} = 0.05$
TLx	$F_{1,28} = 0.96$	$F_{1,28} = 39.16$ **	$F_{1,28} = 7.05$ *	$F_{1,28} = 3.37$	$F_{1,28} = 5.30$ *	$F_{2,56} = 3.66$ *	$F_{2,56} = 0.02$	$F_{2,56} = 11.93$ **	$F_{2,56} = 1.12$
TLy	$F_{1,28} = 0.89$	$F_{1,28} = 29.07$ **	$F_{1,28} = 6.50$ *	$F_{1,28} = 2.19$	$F_{1,28} = 3.57$	$F_{2,56} = 0.96$	$F_{2,56} = 0.17$	$F_{2,56} = 3.98$ *	$F_{2,56} = 0.40$
Vm	$F_{1,28} = 0.77$	$F_{1,28} = 35.16$ **	$F_{1,28} = 7.03$ *	$F_{1,28} = 2.65$	$F_{1,28} = 4.54$ *	$F_{2,56} = 2.26$	$F_{2,56} = 0.01$	$F_{2,56} = 8.49$ **	$F_{2,56} = 0.05$
Vxm	$F_{1,28} = 1.00$	$F_{1,28} = 37.21$ **	$F_{1,28} = 6.51$ *	$F_{1,28} = 3.59$	$F_{1,28} = 5.57$ *	$F_{2,56} = 3.55$ *	$F_{2,56} = 0.01$	$F_{2,56} = 11.65$ **	$F_{2,56} = 1.17$
Vym	$F_{1,28} = 0.86$	$F_{1,28} = 29.07$ **	$F_{1,28} = 6.50$ *	$F_{1,28} = 2.19$	$F_{1,28} = 3.57$	$F_{2,56} = 0.96$	$F_{2,56} = 0.17$	$F_{2,56} = 3.98$ *	$F_{2,56} = 0.40$
Ay	$F_{1,28} = 0.58$	$F_{1,28} = 2.43$	$F_{1,28} = 2.12$	$F_{1,28} = 0.47$	$F_{1,28} = 0.87$	$F_{2,56} = 2.45$	$F_{2,56} = 3.02$	$F_{2,56} = 13.42$ **	$F_{2,56} = 2.28$

Postural Sway Parameter	Vision * Sound	Sex * Vision * Sound	Vision * Neck Rotation	Sex * Vision * Neck Rotation	Vision * Neck F/E	Sex * Vision * Neck F/E	Sound * Neck Rotation	Sex * Sound * Neck Rotation	Sound * Neck F/E
X	$F_{1,28} = 1.44$	$F_{1,28} = 0.74$	$F_{2,56} = 1.86$	$F_{2,56} = 1.02$	$F_{2,56} = 2.43$	$F_{2,56} = 0.90$	$F_{2,56} = 1.06$	$F_{2,56} = 0.66$	$F_{2,56} = 0.96$
Y	$F_{1,28} = 0.04$	$F_{1,28} = 0.01$	$F_{2,56} = 11.63$ **	$F_{2,56} = 2.13$	$F_{2,56} = 1.89$	$F_{2,56} = 1.93$	$F_{2,56} = 1.35$	$F_{2,56} = 3.01$	$F_{2,56} = 1.14$
Sx	$F_{1,28} = 1.18$	$F_{1,28} = 2.07$	$F_{2,56} = 0.98$	$F_{2,56} = 2.59$	$F_{2,56} = 6.39$ **	$F_{2,56} = 3.05$	$F_{2,56} = 0.18$	$F_{2,56} = 1.34$	$F_{2,56} = 0.13$
Sr	$F_{1,28} = 0.04$	$F_{1,28} = 1.48$	$F_{2,56} = 0.88$	$F_{2,56} = 2.09$	$F_{2,56} = 3.44$ *	$F_{2,56} = 2.22$	$F_{2,56} = 0.58$	$F_{2,56} = 1.20$	$F_{2,56} = 1.28$
Sl	$F_{1,28} = 0.42$	$F_{1,28} = 2.29$	$F_{2,56} = 0.88$	$F_{2,56} = 1.86$	$F_{2,56} = 8.38$ **	$F_{2,56} = 3.20$ *	$F_{2,56} = 0.72$	$F_{2,56} = 1.04$	$F_{2,56} = 0.40$
Sy	$F_{1,28} = 0.19$	$F_{1,28} = 0.66$	$F_{2,56} = 0.25$	$F_{2,56} = 1.04$	$F_{2,56} = 8.24$ **	$F_{2,56} = 1.48$	$F_{2,56} = 0.45$	$F_{2,56} = 0.88$	$F_{2,56} = 0.99$
Sa	$F_{1,28} = 0.00$	$F_{1,28} = 1.69$	$F_{2,56} = 0.25$	$F_{2,56} = 0.45$	$F_{2,56} = 6.03$ **	$F_{2,56} = 2.63$	$F_{2,56} = 0.63$	$F_{2,56} = 0.65$	$F_{2,56} = 0.57$
Sp	$F_{1,28} = 0.99$	$F_{1,28} = 0.06$	$F_{2,56} = 0.49$	$F_{2,56} = 1.16$	$F_{2,56} = 9.21$ **	$F_{2,56} = 0.61$	$F_{2,56} = 0.32$	$F_{2,56} = 0.62$	$F_{2,56} = 0.89$
TL	$F_{1,28} = 2.66$	$F_{1,28} = 3.55$	$F_{2,56} = 0.28$	$F_{2,56} = 0.35$	$F_{2,56} = 2.05$	$F_{2,56} = 0.70$	$F_{2,56} = 2.67$	$F_{2,56} = 0.95$	$F_{2,56} = 1.23$
TLx	$F_{1,28} = 3.08$	$F_{1,28} = 3.90$	$F_{2,56} = 0.40$	$F_{2,56} = 0.48$	$F_{2,56} = 1.71$	$F_{2,56} = 1.66$	$F_{2,56} = 2.48$	$F_{2,56} = 0.88$	$F_{2,56} = 0.50$
TLy	$F_{1,28} = 2.51$	$F_{1,28} = 3.30$	$F_{2,56} = 0.39$	$F_{2,56} = 0.16$	$F_{2,56} = 2.10$	$F_{2,56} = 0.09$	$F_{2,56} = 2.49$	$F_{2,56} = 0.99$	$F_{2,56} = 1.65$
Vm	$F_{1,28} = 2.66$	$F_{1,28} = 3.55$	$F_{2,56} = 0.28$	$F_{2,56} = 0.35$	$F_{2,56} = 2.05$	$F_{2,56} = 0.70$	$F_{2,56} = 2.67$	$F_{2,56} = 0.95$	$F_{2,56} = 1.23$
Vxm	$F_{1,28} = 2.82$	$F_{1,28} = 3.61$	$F_{2,56} = 0.32$	$F_{2,56} = 0.59$	$F_{2,56} = 1.85$	$F_{2,56} = 1.57$	$F_{2,56} = 2.59$	$F_{2,56} = 0.83$	$F_{2,56} = 0.42$
Vym	$F_{1,28} = 2.51$	$F_{1,28} = 3.39$	$F_{2,56} = 0.39$	$F_{2,56} = 0.16$	$F_{2,56} = 2.10$	$F_{2,56} = 0.09$	$F_{2,56} = 2.49$	$F_{2,56} = 0.99$	$F_{2,56} = 1.65$
Ay	$F_{1,28} = 1.58$	$F_{1,28} = 0.17$	$F_{2,56} = 3.39$ *	$F_{2,56} = 0.41$	$F_{2,56} = 7.44$ **	$F_{2,56} = 0.41$	$F_{2,56} = 2.94$	$F_{2,56} = 1.12$	$F_{2,56} = 0.51$

Postural Sway Parameter	Sex * Sound * Neck F/E	Neck Rotation * Neck F/E	Sex * Neck Rotation * Neck F/E	Vision * Sound * Neck Rotation	Sex * Vision * Sound * Neck Rotation	Vision * Sound * Neck F/E	Sex * Vision * Sound * Neck F/E	Vision * Neck Rotation * Neck F/E	Sex * Vision * Neck Rotation * Neck F/E
X	$F_{2,56} = 1.71$	$F_{4,112} = 2.47$ *	$F_{4,112} = 0.75$	$F_{2,56} = 2.09$	$F_{2,56} = 0.69$	$F_{2,56} = 1.24$	$F_{2,56} = 1.82$	$F_{4,112} = 1.47$	$F_{4,112} = 0.96$
Y	$F_{2,56} = 0.15$	$F_{4,112} = 2.19$	$F_{4,112} = 2.13$	$F_{2,56} = 2.12$	$F_{2,56} = 0.13$	$F_{2,56} = 2.55$	$F_{2,56} = 0.40$	$F_{4,112} = 0.70$	$F_{4,112} = 0.87$
Sx	$F_{2,56} = 0.79$	$F_{4,112} = 1.44$	$F_{4,112} = 1.59$	$F_{2,56} = 0.35$	$F_{2,56} = 1.44$	$F_{2,56} = 1.40$	$F_{2,56} = 0.08$	$F_{4,112} = 0.70$	$F_{4,112} = 0.70$
Sr	$F_{2,56} = 1.63$	$F_{4,112} = 3.48$ *	$F_{4,112} = 1.15$	$F_{2,56} = 0.12$	$F_{2,56} = 2.81$	$F_{2,56} = 0.40$	$F_{2,56} = 0.65$	$F_{4,112} = 1.04$	$F_{4,112} = 0.20$
Sl	$F_{2,56} = 0.42$	$F_{4,112} = 0.30$	$F_{4,112} = 1.43$	$F_{2,56} = 0.66$	$F_{2,56} = 0.19$	$F_{2,56} = 2.70$	$F_{2,56} = 0.73$	$F_{4,112} = 0.63$	$F_{4,112} = 0.80$
Sy	$F_{2,56} = 0.52$	$F_{4,112} = 1.61$	$F_{4,112} = 0.35$	$F_{2,56} = 1.41$	$F_{2,56} = 2.81$	$F_{2,56} = 1.83$	$F_{2,56} = 0.48$	$F_{4,112} = 1.48$	$F_{4,112} = 0.28$
Sa	$F_{2,56} = 0.59$	$F_{4,112} = 1.07$	$F_{4,112} = 0.33$	$F_{2,56} = 0.16$	$F_{2,56} = 2.36$	$F_{2,56} = 1.82$	$F_{2,56} = 0.08$	$F_{4,112} = 1.24$	$F_{4,112} = 0.57$
Sp	$F_{2,56} = 1.46$	$F_{4,112} = 1.92$	$F_{4,112} = 0.20$	$F_{2,56} = 3.98$ *	$F_{2,56} = 1.09$	$F_{2,56} = 0.72$	$F_{2,56} = 0.65$	$F_{4,112} = 2.00$	$F_{4,112} = 1.11$
TL	$F_{2,56} = 0.33$	$F_{4,112} = 0.99$	$F_{4,112} = 1.05$	$F_{2,56} = 1.25$	$F_{2,56} = 1.26$	$F_{2,56} = 0.44$	$F_{2,56} = 0.95$	$F_{4,112} = 0.80$	$F_{4,112} = 0.28$
TLx	$F_{2,56} = 0.73$	$F_{4,112} = 1.20$	$F_{4,112} = 0.91$	$F_{2,56} = 1.08$	$F_{2,56} = 0.73$	$F_{2,56} = 0.64$	$F_{2,56} = 0.43$	$F_{4,112} = 1.21$	$F_{4,112} = 0.19$
TLy	$F_{2,56} = 0.90$	$F_{4,112} = 0.81$	$F_{4,112} = 0.92$	$F_{2,56} = 1.18$	$F_{2,56} = 1.70$	$F_{2,56} = 0.77$	$F_{2,56} = 1.27$	$F_{4,112} = 0.42$	$F_{4,112} = 0.46$
Vm	$F_{2,56} = 0.33$	$F_{4,112} = 0.99$	$F_{4,112} = 1.05$	$F_{2,56} = 1.25$	$F_{2,56} = 1.26$	$F_{2,56} = 0.42$	$F_{2,56} = 0.95$	$F_{4,112} = 0.80$	$F_{4,112} = 0.28$
Vxm	$F_{2,56} = 0.92$	$F_{4,112} = 1.07$	$F_{4,112} = 0.95$	$F_{2,56} = 1.18$	$F_{2,56} = 0.77$	$F_{2,56} = 0.51$	$F_{2,56} = 0.60$	$F_{4,112} = 1.08$	$F_{4,112} = 0.21$
Vym	$F_{2,56} = 0.90$	$F_{4,112} = 0.81$	$F_{4,112} = 0.92$	$F_{2,56} = 1.18$	$F_{2,56} = 1.70$	$F_{2,56} = 0.77$	$F_{2,56} = 1.27$	$F_{4,112} = 0.42$	$F_{4,112} = 0.46$
Ay	$F_{2,56} = 0.41$	$F_{4,112} = 1.07$	$F_{4,112} = 3.22$ *	$F_{2,56} = 1.33$	$F_{2,56} = 1.07$	$F_{2,56} = 0.01$	$F_{2,56} = 0.36$	$F_{4,112} = 0.93$	$F_{4,112} = 0.51$

Postural Sway Parameter	Sound * Neck Rotation * Neck F/E	Sex * Sound * Neck Rotation * Neck F/E	Vision * Sound * Neck Rotation * Neck F/E	Sex * Vision * Sound * Neck Rotation * Neck F/E
X	$F_{4,112}$ = 0.26	$F_{4,112}$ = 0.31	$F_{4,112}$ = 0.60	$F_{4,112}$ = 1.08
Y	$F_{4,112}$ = 0.02	$F_{4,112}$ = 0.24	$F_{4,112}$ = 0.54	$F_{4,112}$ = 1.32
Sx	$F_{4,112}$ = 2.23	$F_{4,112}$ = 3.55 *	$F_{4,112}$ = 1.60	$F_{4,112}$ = 0.47
Sr	$F_{4,112}$ = 0.43	$F_{4,112}$ = 2.10	$F_{4,112}$ = 1.30	$F_{4,112}$ = 1.43
Sl	$F_{4,112}$ = 2.20	$F_{4,112}$ = 1.91	$F_{4,112}$ = 1.12	$F_{4,112}$ = 0.46
Sy	$F_{4,112}$ = 0.49	$F_{4,112}$ = 1.24	$F_{4,112}$ = 0.64	$F_{4,112}$ = 0.41
Sa	$F_{4,112}$ = 0.39	$F_{4,112}$ = 1.28	$F_{4,112}$ = 0.26	$F_{4,112}$ = 0.32
Sp	$F_{4,112}$ = 0.68	$F_{4,112}$ = 2.22	$F_{4,112}$ = 1.59	$F_{4,112}$ = 0.85
TL	$F_{4,112}$ = 1.08	$F_{4,112}$ = 1.15	$F_{4,112}$ = 0.21	$F_{4,112}$ = 1.64
TLx	$F_{4,112}$ = 1.36	$F_{4,112}$ = 1.64	$F_{4,112}$ = 0.53	$F_{4,112}$ = 2.65 *
TLy	$F_{4,112}$ = 0.73	$F_{4,112}$ = 0.74	$F_{4,112}$ = 0.19	$F_{4,112}$ = 0.82
Vm	$F_{4,112}$ = 1.08	$F_{4,112}$ = 1.15	$F_{4,112}$ = 0.21	$F_{4,112}$ = 1.64
Vxm	$F_{4,112}$ = 1.47	$F_{4,112}$ = 1.62	$F_{4,112}$ = 0.61	$F_{4,112}$ = 2.36
Vym	$F_{4,112}$ = 0.73	$F_{4,112}$ = 0.73	$F_{4,112}$ = 0.19	$F_{4,112}$ = 0.82
Ay	$F_{4,112}$ = 1.79	$F_{4,112}$ = 0.97	$F_{4,112}$ = 3.20 *	$F_{4,112}$ = 0.58

* $p<0.05$, ** $p<0.01$ significant influence on each variable or combination of variables on each postural sway parameter.

Table A8.1 The influence of sex, vision, sound, neck rotation and neck flexion/extension and their interactions on the various parameters of postural sway behaviour.

Appendix 9: Analyses of variance for Chapter 8: Experiment 4.

Postural Sway Parameter	Sex	Sound	Sex * Sound	Velocity of Head Movement (Velocity)	Sex * Velocity	Direction of Head Movement (Direction)	Sex * Direction	Sound * Velocity
X	$F_{1,28} = 8.28$ **	$F_{1,28} = 1.29$	$F_{1,28} = 0.07$	$F_{1,28} = 0.50$	$F_{1,28} = 0.35$	$F_{7,196} = 0.99$	$F_{7,196} = 0.45$	$F_{1,28} = 3.24$
Y	$F_{1,28} = 0.05$	$F_{1,28} = 0.25$	$F_{1,28} = 0.02$	$F_{1,28} = 2.09$	$F_{1,28} = 0.18$	$F_{7,196} = 2.72$ *	$F_{7,196} = 2.03$	$F_{1,28} = 0.03$
Sx	$F_{1,28} = 0.00$	$F_{1,28} = 2.74$	$F_{1,28} = 0.38$	$F_{1,28} = 17.42$ **	$F_{1,28} = 1.93$	$F_{7,196} = 3.26$ **	$F_{7,196} = 0.46$	$F_{1,28} = 0.09$
Sr	$F_{1,28} = 0.00$	$F_{1,28} = 2.95$	$F_{1,28} = 0.18$	$F_{1,28} = 15.19$ **	$F_{1,28} = 1.31$	$F_{7,196} = 2.92$ **	$F_{7,196} = 0.34$	$F_{1,28} = 0.01$
Sl	$F_{1,28} = 0.00$	$F_{1,28} = 2.31$	$F_{1,28} = 0.55$	$F_{1,28} = 17.51$ **	$F_{1,28} = 2.33$	$F_{7,196} = 3.25$ **	$F_{7,196} = 0.62$	$F_{1,28} = 0.15$
Sy	$F_{1,28} = 0.04$	$F_{1,28} = 1.30$	$F_{1,28} = 0.00$	$F_{1,28} = 84.97$ **	$F_{1,28} = 3.52$	$F_{7,196} = 12.10$ **	$F_{7,196} = 0.32$	$F_{1,28} = 2.17$
Sa	$F_{1,28} = 0.07$	$F_{1,28} = 3.56$	$F_{1,28} = 2.34$	$F_{1,28} = 82.96$ **	$F_{1,28} = 1.72$	$F_{7,196} = 14.51$ **	$F_{7,196} = 0.39$	$F_{1,28} = 0.00$
Sp	$F_{1,28} = 0.02$	$F_{1,28} = 0.03$	$F_{1,28} = 1.45$	$F_{1,28} = 59.88$ **	$F_{1,28} = 4.40$ *	$F_{7,196} = 8.25$ **	$F_{7,196} = 0.31$	$F_{1,28} = 5.24$ *
TL	$F_{1,28} = 1.26$	$F_{1,28} = 3.50$	$F_{1,28} = 1.06$	$F_{1,28} = 28.82$ **	$F_{1,28} = 2.18$	$F_{7,196} = 4.89$ **	$F_{7,196} = 0.52$	$F_{1,28} = 1.21$
TLx	$F_{1,28} = 1.45$	$F_{1,28} = 1.82$	$F_{1,28} = 1.68$	$F_{1,28} = 16.22$ **	$F_{1,28} = 2.74$	$F_{7,196} = 3.02$ **	$F_{7,196} = 0.77$	$F_{1,28} = 0.81$
TLy	$F_{1,28} = 1.39$	$F_{1,28} = 3.58$	$F_{1,28} = 0.33$	$F_{1,28} = 37.92$ **	$F_{1,28} = 1.26$	$F_{7,196} = 8.67$ **	$F_{7,196} = 0.46$	$F_{1,28} = 0.42$
Vm	$F_{1,28} = 1.26$	$F_{1,28} = 3.50$	$F_{1,28} = 1.06$	$F_{1,28} = 28.82$ **	$F_{1,28} = 2.18$	$F_{7,196} = 4.89$ **	$F_{7,196} = 0.52$	$F_{1,28} = 1.21$
Vxm	$F_{1,28} = 1.45$	$F_{1,28} = 1.82$	$F_{1,28} = 1.68$	$F_{1,28} = 16.22$ **	$F_{1,28} = 2.74$	$F_{7,196} = 3.02$ **	$F_{7,196} = 0.77$	$F_{1,28} = 0.81$
Vym	$F_{1,28} = 1.39$	$F_{1,28} = 3.58$	$F_{1,28} = 0.33$	$F_{1,28} = 37.92$ **	$F_{1,28} = 1.26$	$F_{7,196} = 8.67$ **	$F_{7,196} = 0.46$	$F_{1,28} = 0.42$
Ay	$F_{1,28} = 0.54$	$F_{1,28} = 0.01$	$F_{1,28} = 1.63$	$F_{1,28} = 2.46$	$F_{1,28} = 2.17$	$F_{7,196} = 1.84$	$F_{7,196} = 0.50$	$F_{1,28} = 0.01$

Postural Sway Parameter	Sex * Sound * Velocity	Sound * Direction	Sex * Sound * Direction	Velocity * Direction	Sex * Velocity * Direction	Sound * Velocity * Direction	Sex * Sound * Velocity * Direction
X	$F_{1,28} = 0.04$	$F_{7,196} = 1.87$	$F_{7,196} = 1.58$	$F_{7,196} = 1.03$	$F_{7,196} = 0.51$	$F_{7,196} = 1.51$	$F_{7,196} = 0.38$
Y	$F_{1,28} = 0.01$	$F_{7,196} = 1.30$	$F_{7,196} = 1.41$	$F_{7,196} = 1.77$	$F_{7,196} = 0.48$	$F_{7,196} = 0.56$	$F_{7,196} = 0.84$
Sx	$F_{1,28} = 0.07$	$F_{7,196} = 4.31$ **	$F_{7,196} = 0.21$	$F_{7,196} = 1.69$	$F_{7,196} = 0.39$	$F_{7,196} = 1.28$	$F_{7,196} = 0.31$
Sr	$F_{1,28} = 0.39$	$F_{7,196} = 3.86$ **	$F_{7,196} = 0.11$	$F_{7,196} = 1.79$	$F_{7,196} = 0.56$	$F_{7,196} = 1.33$	$F_{7,196} = 0.49$
Sl	$F_{1,28} = 0.02$	$F_{7,196} = 3.56$ **	$F_{7,196} = 0.48$	$F_{7,196} = 1.27$	$F_{7,196} = 0.57$	$F_{7,196} = 1.01$	$F_{7,196} = 0.27$
Sy	$F_{1,28} = 0.77$	$F_{7,196} = 0.76$	$F_{7,196} = 0.76$	$F_{7,196} = 9.84$ **	$F_{7,196} = 0.93$	$F_{7,196} = 0.67$	$F_{7,196} = 1.03$
Sa	$F_{1,28} = 0.07$	$F_{7,196} = 1.14$	$F_{7,196} = 1.46$	$F_{7,196} = 10.84$ **	$F_{7,196} = 1.20$	$F_{7,196} = 1.15$	$F_{7,196} = 1.06$
Sp	$F_{1,28} = 1.31$	$F_{7,196} = 0.58$	$F_{7,196} = 0.65$	$F_{7,196} = 5.42$ **	$F_{7,196} = 1.15$	$F_{7,196} = 0.79$	$F_{7,196} = 0.84$
TL	$F_{1,28} = 0.19$	$F_{7,196} = 1.86$	$F_{7,196} = 0.19$	$F_{7,196} = 2.86$ **	$F_{7,196} = 1.19$	$F_{7,196} = 1.64$	$F_{7,196} = 1.15$
TLx	$F_{1,28} = 0.68$	$F_{7,196} = 3.31$ **	$F_{7,196} = 0.22$	$F_{7,196} = 1.05$	$F_{7,196} = 0.80$	$F_{7,196} = 1.50$	$F_{7,196} = 1.15$
TLy	$F_{1,28} = 1.60$	$F_{7,196} = 1.06$	$F_{7,196} = 0.44$	$F_{7,196} = 7.53$ **	$F_{7,196} = 1.85$	$F_{7,196} = 1.25$	$F_{7,196} = 0.67$
Vm	$F_{1,28} = 0.19$	$F_{7,196} = 1.86$	$F_{7,196} = 0.19$	$F_{7,196} = 2.86$ **	$F_{7,196} = 1.19$	$F_{7,196} = 1.64$	$F_{7,196} = 1.15$
Vxm	$F_{1,28} = 0.68$	$F_{7,196} = 3.31$ **	$F_{7,196} = 0.22$	$F_{7,196} = 1.05$	$F_{7,196} = 0.80$	$F_{7,196} = 1.50$	$F_{7,196} = 1.15$
Vym	$F_{1,28} = 1.60$	$F_{7,196} = 1.06$	$F_{7,196} = 0.44$	$F_{7,196} = 7.53$ **	$F_{7,196} = 1.85$	$F_{7,196} = 1.25$	$F_{7,196} = 0.67$
Ay	$F_{1,28} = 0.03$	$F_{7,196} = 1.71$	$F_{7,196} = 0.87$	$F_{7,196} = 1.60$	$F_{7,196} = 0.86$	$F_{7,196} = 1.14$	$F_{7,196} = 0.98$

* $p<0.05$, ** $p<0.01$ significant on each variable or combination of variables on each postural sway parameter.

Table A9.1 The influence of sex, sound, velocity and direction of head movement and their interactions on the various parameters of postural sway behaviour.

Appendix 10: Analyses of variance for Chapter 9.

Postural Sway Parameter	Sex	Sound	Sex * Sound	Condition of Head (Condition)	Sex * Condition	Direction of Head Movement (Direction)	Sex * Direction	Sound * Condition
X	$F_{1,28} = 8.71$ **	$F_{1,28} = 0.40$	$F_{1,28} = 0.01$	$F_{2,56} = 1.38$	$F_{2,56} = 1.27$	$F_{7,196} = 1.16$	$F_{7,196} = 0.46$	$F_{2,56} = 0.65$
Y	$F_{1,28} = 0.02$	$F_{1,28} = 1.12.$	$F_{1,28} = 0.08$	$F_{2,56} = 0.69$	$F_{2,56} = 0.17$	$F_{7,196} = 3.37$ **	$F_{7,196} = 2.83$ **	$F_{2,56} = 1.45$
Sx	$F_{1,28} = 0.00$	$F_{1,28} = 0.39$	$F_{1,28} = 1.32$	$F_{2,56} = 32.38$ **	$F_{2,56} = 0.37$	$F_{7,196} = 2.40$ **	$F_{7,196} = 0.50$	$F_{2,56} = 3.73$ *
Sr	$F_{1,28} = 0.00$	$F_{1,28} = 0.37$	$F_{1,28} = 0.08$	$F_{2,56} = 10.45$ **	$F_{2,56} = 0.15$	$F_{7,196} = 2.12$ *	$F_{7,196} = 0.40$	$F_{2,56} = 3.23$ *
Sl	$F_{1,28} = 0.00$	$F_{1,28} = 0.33$	$F_{1,28} = 1.68$	$F_{2,56} = 37.85$ **	$F_{2,56} = 0.45$	$F_{7,196} = 2.46$ *	$F_{7,196} = 0.68$	$F_{2,56} = 3.61$ *
Sy	$F_{1,28} = 0.03$	$F_{1,28} = 0.01$	$F_{1,28} = 1.14$	$F_{2,56} = 96.63$ **	$F_{2,56} = 0.70$	$F_{7,196} = 11.33$ **	$F_{7,196} = 0.38$	$F_{2,56} = 2.13$
Sa	$F_{1,28} = 0.07$	$F_{1,28} = 0.01$	$F_{1,28} = 3.32$	$F_{2,56} = 102.53$ **	$F_{2,56} = 0.40$	$F_{7,196} = 13.41$ **	$F_{7,196} = 0.50$	$F_{2,56} = 3.22$ *
Sp	$F_{1,28} = 0.01$	$F_{1,28} = 0.06$	$F_{1,28} = 0.08$	$F_{2,56} = 81.94$ **	$F_{2,56} = 0.97$	$F_{7,196} = 7.93$ **	$F_{7,196} = 0.34$	$F_{2,56} = 1.85$
TL	$F_{1,28} = 0.97$	$F_{1,28} = 0.05$	$F_{1,28} = 1.34$	$F_{2,56} = 9.18$ **	$F_{2,56} = 60$	$F_{7,196} = 4.33$ **	$F_{7,196} = 0.40$	$F_{2,56} = 0.72$
TLx	$F_{1,28} = 1.20$	$F_{1,28} = 0.02$	$F_{1,28} = 1.05$	$F_{2,56} = 9.10$ **	$F_{2,56} = 0.55$	$F_{7,196} = 3.33$ **	$F_{7,196} = 0.55$	$F_{2,56} = 1.55$
TLy	$F_{1,28} = 1.08$	$F_{1,28} = 0.01$	$F_{1,28} = 1.28$	$F_{2,56} = 10.17$ **	$F_{2,56} = 0.71$	$F_{7,196} = 7.48$ **	$F_{7,196} = 0.35$	$F_{2,56} = 1.83$
Vm	$F_{1,28} = 0.97$	$F_{1,28} = 0.05$	$F_{1,28} = 1.34$	$F_{2,56} = 9.18$ **	$F_{2,56} = 0.60$	$F_{7,196} = 4.33$ **	$F_{7,196} = 0.40$	$F_{2,56} = 0.72$
Vxm	$F_{1,28} = 1.22$	$F_{1,28} = 0.08$	$F_{1,28} = 1.58$	$F_{2,56} = 8.58$ **	$F_{2,56} = 0.53$	$F_{7,196} = 3.82$ **	$F_{7,196} = 0.65$	$F_{2,56} = 0.59$
Vym	$F_{1,28} = 1.08$	$F_{1,28} = 0.01$	$F_{1,28} = 1.08$	$F_{2,56} = 10.17$ **	$F_{2,56} = 0.71$	$F_{7,196} = 7.48$ **	$F_{7,196} = 0.35$	$F_{2,56} = 0.83$
Ay	$F_{1,28} = 0.00$	$F_{1,28} = 0.00$	$F_{1,28} = 1.08$	$F_{2,56} = 0.15$	$F_{2,56} = 2.99$	$F_{7,196} = 1.80$	$F_{7,196} = 0.56$	$F_{2,56} = 0.00$

Postural Sway Parameter	Sex * Sound * Condition	Sound * Direction	Sex * Sound * Direction	Condition * Direction	Sex * Condition * Direction	Sound * Condition * Direction	Sex * Sound * Condition * Direction
X	$F_{2,56}$ = 0.00	$F_{7,196}$ = 1.59	$F_{7,196}$ = 2.22 *	$F_{14,392}$ = 1.29	$F_{14,392}$ = 0.42	$F_{14,392}$ = 1.69	$F_{14,392}$ = 0.42
Y	$F_{2,56}$ = 0.55	$F_{7,196}$ = 1.66	$F_{7,196}$ = 1.02	$F_{14,392}$ = 2.07 *	$F_{14,392}$ = 0.98	$F_{14,392}$ = 0.93	$F_{14,392}$ = 1.00
Sx	$F_{2,56}$ = 0.12	$F_{7,196}$ = 4.21 **	$F_{7,196}$ = 0.50	$F_{14,392}$ = 3.11 **	$F_{14,392}$ = 0.50	$F_{14,392}$ = 1.65	$F_{14,392}$ = 0.49
Sr	$F_{2,56}$ = 0.22	$F_{7,196}$ = 3.18 **	$F_{7,196}$ = 0.53	$F_{14,392}$ = 2.71 **	$F_{14,392}$ = 0.57	$F_{14,392}$ = 1.68	$F_{14,392}$ = 0.78
Sl	$F_{2,56}$ = 0.05	$F_{7,196}$ = 4.22 **	$F_{7,196}$ = 0.63	$F_{14,392}$ = 2.88 **	$F_{14,392}$ = 0.63	$F_{14,392}$ = 1.25	$F_{14,392}$ = 0.33
Sv	$F_{2,56}$ = 1.28	$F_{7,196}$ = 0.89	$F_{7,196}$ = 1.13	$F_{14,392}$ = 10.74 **	$F_{14,392}$ = 0.67	$F_{14,392}$ = 0.76	$F_{14,392}$ = 0.86
Sa	$F_{2,56}$ = 0.02	$F_{7,196}$ = 1.11	$F_{7,196}$ = 1.89	$F_{14,392}$ = 12.24 **	$F_{14,392}$ = 0.83	$F_{14,392}$ = 1.21	$F_{14,392}$ = 1.00
Sμ	$F_{2,56}$ = 3.51 *	$F_{7,196}$ = 0.67	$F_{7,196}$ = 0.91	$F_{14,392}$ = 6.34 **	$F_{14,392}$ = 0.88	$F_{14,392}$ = 0.80	$F_{14,392}$ = 0.69
TL	$F_{2,56}$ = 0.31	$F_{7,196}$ = 1.42	$F_{7,196}$ = 0.45	$F_{14,392}$ = 3.00 **	$F_{14,392}$ = 0.60	$F_{14,392}$ = 2.27 **	$F_{14,392}$ = 0.99
TLx	$F_{2,56}$ = 0.18	$F_{7,196}$ = 0.77	$F_{7,196}$ = 0.64	$F_{14,392}$ = 4.96 **	$F_{14,392}$ = 0.55	$F_{14,392}$ = 2.30 **	$F_{14,392}$ = 0.78
TLy	$F_{2,56}$ = 0.70	$F_{7,196}$ = 1.04	$F_{7,196}$ = 0.75	$F_{14,392}$ = 6.22 **	$F_{14,392}$ = 0.90	$F_{14,392}$ = 1.94 *	$F_{14,392}$ = 0.79
Vm	$F_{2,56}$ = 0.31	$F_{7,196}$ = 1.42	$F_{7,196}$ = 0.45	$F_{14,392}$ = 3.00 **	$F_{14,392}$ = 0.60	$F_{14,392}$ = 2.27 **	$F_{14,392}$ = 0.99
Vxm	$F_{2,56}$ = 0.13	$F_{7,196}$ = 1.98	$F_{7,196}$ = 0.50	$F_{14,392}$ = 3.96 **	$F_{14,392}$ = 0.48	$F_{14,392}$ = 2.31 **	$F_{14,392}$ = 0.92
Vym	$F_{2,56}$ = 0.70	$F_{7,196}$ = 1.04	$F_{7,196}$ = 0.75	$F_{14,392}$ = 6.22 **	$F_{14,392}$ = 0.90	$F_{14,392}$ = 1.94 *	$F_{14,392}$ = 0.79
Ay	$F_{2,56}$ = 0.15	$F_{7,196}$ = 1.44	$F_{7,196}$ = 1.00	$F_{14,392}$ = 2.23 **	$F_{14,392}$ = 1.13	$F_{14,392}$ = 1.74 *	$F_{14,392}$ = 0.76

* $p<0.05$, ** $p<0.01$ significant influence on each variable or combination of variables on each postural sway parameter.

Table A10.1 The influence of sex, sound, the condition of head (static/dynamic) and the direction of head movement and their interactions on the various parameters of postural sway behaviour.

Appendix 11: Analyses of variance for Chapter 10.

Postural Sway Parameter	Sex	Vision	Sex * Vision	Sound	Sex * Sound	Neck Rotation	Sex * Neck Rotation	Neck Flexion/ Extension (Neck F/E)
X	$F_{1,19} = 10.71$ **	$F_{1,19} = 3.64$	$F_{1,19} = 1.21$	$F_{2,38} = 5.44$ **	$F_{2,38} = 0.10$	$F_{2,38} = 7.95$ **	$F_{2,38} = 0.13$	$F_{2,38} = 0.38$
Y	$F_{1,19} = 1.13$	$F_{1,19} = 3.23$	$F_{1,19} = 4.30$	$F_{2,38} = 4.86$ *	$F_{2,38} = 1.01$	$F_{2,38} = 2.19$	$F_{2,38} = 1.47$	$F_{2,38} = 2.15$
Sx	$F_{1,19} = 0.10$	$F_{1,19} = 65.50$ **	$F_{1,19} = 1.59$	$F_{2,38} = 23.68$ **	$F_{2,38} = 0.42$	$F_{2,38} = 1.58$	$F_{2,38} = 0.60$	$F_{2,38} = 4.71$ *
Sr	$F_{1,19} = 0.05$	$F_{1,19} = 50.28$ **	$F_{1,19} = 0.82$	$F_{2,38} = 24.09$ **	$F_{2,38} = 0.28$	$F_{2,38} = 1.14$	$F_{2,38} = 1.10$	$F_{2,38} = 4.17$ *
Sl	$F_{1,19} = 0.16$	$F_{1,19} = 75.46$ **	$F_{1,19} = 2.63$	$F_{2,38} = 22.21$ **	$F_{2,38} = 0.62$	$F_{2,38} = 1.66$	$F_{2,38} = 0.18$	$F_{2,38} = 3.33$ *
Sy	$F_{1,19} = 0.09$	$F_{1,19} = 54.28$ **	$F_{1,19} = 0.72$	$F_{2,38} = 31.65$ **	$F_{2,38} = 1.50$	$F_{2,38} = 0.48$	$F_{2,38} = 2.87$	$F_{2,38} = 7.01$ **
Sa	$F_{1,19} = 0.05$	$F_{1,19} = 63.70$ **	$F_{1,19} = 0.89$	$F_{2,38} = 31.93$ **	$F_{2,38} = 1.56$	$F_{2,38} = 0.76$	$F_{2,38} = 2.12$	$F_{2,38} = 5.65$ **
Sp	$F_{1,19} = 0.18$	$F_{1,19} = 45.17$ **	$F_{1,19} = 0.73$	$F_{2,38} = 29.27$ **	$F_{2,38} = 1.62$	$F_{2,38} = 0.01$	$F_{2,38} = 4.73$ *	$F_{2,38} = 7.37$ **
TL	$F_{1,19} = 0.72$	$F_{1,19} = 23.43$ **	$F_{1,19} = 4.17$	$F_{2,38} = 16.76$ **	$F_{2,38} = 1.13$	$F_{2,38} = 2.67$	$F_{2,38} = 0.04$	$F_{2,38} = 4.37$ *
TLx	$F_{1,19} = 0.54$	$F_{1,19} = 26.61$ **	$F_{1,19} = 3.76$	$F_{2,38} = 15.70$ **	$F_{2,38} = 1.18$	$F_{2,38} = 3.93$ *	$F_{2,38} = 0.18$	$F_{2,38} = 7.89$ **
TLy	$F_{1,19} = 0.56$	$F_{1,19} = 19.41$ **	$F_{1,19} = 4.47$ *	$F_{2,38} = 12.82$ **	$F_{2,38} = 1.25$	$F_{2,38} = 1.46$	$F_{2,38} = 0.08$	$F_{2,38} = 1.51$
Vm	$F_{1,19} = 1.86$	$F_{1,19} = 18.20$ **	$F_{1,19} = 3.91$	$F_{2,38} = 47.68$ **	$F_{2,38} = 0.80$	$F_{2,38} = 2.73$	$F_{2,38} = 0.04$	$F_{2,38} = 3.82$ *
Vxm	$F_{1,19} = 0.71$	$F_{1,19} = 18.69$ **	$F_{1,19} = 3.12$	$F_{2,38} = 50.80$ **	$F_{2,38} = 0.89$	$F_{2,38} = 3.82$ *	$F_{2,38} = 0.14$	$F_{2,38} = 7.06$ **
Vym	$F_{1,19} = 0.60$	$F_{1,19} = 15.53$ **	$F_{1,19} = 4.22$ *	$F_{2,38} = 37.10$ **	$F_{2,38} = 0.92$	$F_{2,38} = 1.51$	$F_{2,38} = 0.03$	$F_{2,38} = 1.26$
Ay	$F_{1,19} = 0.14$	$F_{1,19} = 0.50$	$F_{1,19} = 0.58$	$F_{2,38} = 14.89$ **	$F_{2,38} = 1.33$	$F_{2,38} = 1.67$	$F_{2,38} = 1.39$	$F_{2,38} = 6.18$ **

Postural Sway Parameter	Sex * Neck F/E	Vision * Sound	Sex * Vision * Sound	Vision * Neck Rotation	Sex * Vision * Neck Rotation	Vision * Neck F/E	Sex * Vision * Neck F/E	Sound * Neck Rotation
X	$F_{2,38}$ = 0.27	$F_{2,38}$ = 3.81 *	$F_{2,38}$ = 0.44	$F_{2,38}$ = 0.64	$F_{2,38}$ = 0.09	$F_{2,38}$ = 2.11	$F_{2,38}$ = 1.93	$F_{4,76}$ = 1.83
Y	$F_{2,38}$ = 1.43	$F_{2,38}$ = 0.18	$F_{2,38}$ = 0.41	$F_{2,38}$ = 10.87 **	$F_{2,38}$ = 0.55	$F_{2,38}$ = 1.31	$F_{2,38}$ = 1.22	$F_{4,76}$ = 3.49 *
Sx	$F_{2,38}$ = 0.04	$F_{2,38}$ = 0.28	$F_{2,38}$ = 1.92	$F_{2,38}$ = 0.10	$F_{2,38}$ = 1.16	$F_{2,38}$ = 3.03	$F_{2,38}$ = 2.53	$F_{4,76}$ = 0.96
Sr	$F_{2,38}$ = 0.30	$F_{2,38}$ = 0.08	$F_{2,38}$ = 1.28	$F_{2,38}$ = 0.25	$F_{2,38}$ = 0.82	$F_{2,38}$ = 1.68	$F_{2,38}$ = 2.11	$F_{4,76}$ = 0.67
Sl	$F_{2,38}$ = 0.07	$F_{2,38}$ = 0.72	$F_{2,38}$ = 2.31	$F_{2,38}$ = 0.49	$F_{2,38}$ = 1.11	$F_{2,38}$ = 3.54 *	$F_{2,38}$ = 2.54	$F_{4,76}$ = 1.36
Sy	$F_{2,38}$ = 0.10	$F_{2,38}$ = 0.61	$F_{2,38}$ = 0.99	$F_{2,38}$ = 0.87	$F_{2,38}$ = 0.51	$F_{2,38}$ = 5.83 *	$F_{2,38}$ = 0.76	$F_{4,76}$ = 1.08
Sa	$F_{2,38}$ = 0.02	$F_{2,38}$ = 1.46	$F_{2,38}$ = 2.20	$F_{2,38}$ = 0.91	$F_{2,38}$ = 1.29	$F_{2,38}$ = 3.66 *	$F_{2,38}$ = 1.51	$F_{4,76}$ = 1.18
Sp	$F_{2,38}$ = 0.79	$F_{2,38}$ = 0.09	$F_{2,38}$ = 0.44	$F_{2,38}$ = 0.64	$F_{2,38}$ = 0.06	$F_{2,38}$ = 7.20 **	$F_{2,38}$ = 0.28	$F_{4,76}$ = 0.80
TL	$F_{2,38}$ = 0.05	$F_{2,38}$ = 2.86	$F_{2,38}$ = 3.16	$F_{2,38}$ = 0.94	$F_{2,38}$ = 0.09	$F_{2,38}$ = 1.00	$F_{2,38}$ = 0.19	$F_{4,76}$ = 2.36
TLx	$F_{2,38}$ = 1.08	$F_{2,38}$ = 2.86	$F_{2,38}$ = 3.15	$F_{2,38}$ = 0.60	$F_{2,38}$ = 0.13	$F_{2,38}$ = 0.80	$F_{2,38}$ = 0.87	$F_{4,76}$ = 2.77 *
TLy	$F_{2,38}$ = 0.46	$F_{2,38}$ = 3.23	$F_{2,38}$ = 3.44 *	$F_{2,38}$ = 1.29	$F_{2,38}$ = 0.22	$F_{2,38}$ = 1.30	$F_{2,38}$ = 0.07	$F_{4,76}$ = 1.87
Vm	$F_{2,38}$ = 0.06	$F_{2,38}$ = 4.82 *	$F_{2,38}$ = 3.34 *	$F_{2,38}$ = 0.75	$F_{2,38}$ = 0.08	$F_{2,38}$ = 0.85	$F_{2,38}$ = 0.22	$F_{4,76}$ = 2.33
Vxm	$F_{2,38}$ = 1.07	$F_{2,38}$ = 4.91 *	$F_{2,38}$ = 2.99	$F_{2,38}$ = 0.43	$F_{2,38}$ = 0.22	$F_{2,38}$ = 0.83	$F_{2,38}$ = 0.76	$F_{4,76}$ = 2.70 *
Vym	$F_{2,38}$ = 0.50	$F_{2,38}$ = 5.08 *	$F_{2,38}$ = 3.65 *	$F_{2,38}$ = 1.11	$F_{2,38}$ = 0.20	$F_{2,38}$ = 1.11	$F_{2,38}$ = 0.09	$F_{4,76}$ = 1.84
Ay	$F_{2,38}$ = 1.24	$F_{2,38}$ = 1.90	$F_{2,38}$ = 0.35	$F_{2,38}$ = 2.65	$F_{2,38}$ = 1.22	$F_{2,38}$ = 3.50 *	$F_{2,38}$ = 0.60	$F_{4,76}$ = 0.97

Postural Sway Parameter	Sex * Sound * Neck Rotation	Sound * Neck F/E	Sex * Sound * Neck F/E	Neck Rotation * Neck F/E	Sex * Neck Rotation * Neck F/E	Vision * Sound * Neck Rotation	Sex * Vision * Sound * Neck Rotation	Vision * Sound * Neck F/E
X	$F_{4,76} = 0.51$	$F_{4,76} = 0.24$	$F_{4,76} = 0.93$	$F_{4,76} = 0.59$	$F_{4,76} = 0.89$	$F_{4,76} = 1.29$	$F_{4,76} = 0.97$	$F_{4,76} = 0.60$
Y	$F_{4,76} = 3.21$ *	$F_{4,76} = 7.83$ **	$F_{4,76} = 0.74$	$F_{4,76} = 2.30$	$F_{4,76} = 1.94$	$F_{4,76} = 3.42$ *	$F_{4,76} = 0.28$	$F_{4,76} = 0.65$
Sx	$F_{4,76} = 1.74$	$F_{4,76} = 0.88$	$F_{4,76} = 0.92$	$F_{4,76} = 1.56$	$F_{4,76} = 1.30$	$F_{4,76} = 1.76$	$F_{4,76} = 1.69$	$F_{4,76} = 1.95$
Sr	$F_{4,76} = 1.38$	$F_{4,76} = 2.06$	$F_{4,76} = 1.37$	$F_{4,76} = 4.29$ **	$F_{4,76} = 1.25$	$F_{4,76} = 1.10$	$F_{4,76} = 2.38$	$F_{4,76} = 0.79$
Sl	$F_{4,76} = 1.98$	$F_{4,76} = 0.44$	$F_{4,76} = 0.72$	$F_{4,76} = 0.32$	$F_{4,76} = 1.07$	$F_{4,76} = 2.34$	$F_{4,76} = 0.84$	$F_{4,76} = 3.34$ *
Sy	$F_{4,76} = 1.00$	$F_{4,76} = 1.48$	$F_{4,76} = 0.77$	$F_{4,76} = 1.19$	$F_{4,76} = 1.31$	$F_{4,76} = 1.45$	$F_{4,76} = 1.50$	$F_{4,76} = 1.16$
Sa	$F_{4,76} = 1.03$	$F_{4,76} = 0.59$	$F_{4,76} = 0.69$	$F_{4,76} = 1.17$	$F_{4,76} = 0.65$	$F_{4,76} = 0.16$	$F_{4,76} = 1.63$	$F_{4,76} = 0.93$
Sp	$F_{4,76} = 0.73$	$F_{4,76} = 2.11$	$F_{4,76} = 1.39$	$F_{4,76} = 1.07$	$F_{4,76} = 1.50$	$F_{4,76} = 2.41$	$F_{4,76} = 0.52$	$F_{4,76} = 0.60$
TL	$F_{4,76} = 1.02$	$F_{4,76} = 1.48$	$F_{4,76} = 0.56$	$F_{4,76} = 0.57$	$F_{4,76} = 1.58$	$F_{4,76} = 1.46$	$F_{4,76} = 1.07$	$F_{4,76} = 0.33$
TLx	$F_{4,76} = 0.96$	$F_{4,76} = 1.43$	$F_{4,76} = 1.34$	$F_{4,76} = 1.04$	$F_{4,76} = 1.46$	$F_{4,76} = 1.56$	$F_{4,76} = 0.84$	$F_{4,76} = 0.41$
TLy	$F_{4,76} = 1.08$	$F_{4,76} = 1.07$	$F_{4,76} = 0.69$	$F_{4,76} = 0.34$	$F_{4,76} = 1.40$	$F_{4,76} = 1.19$	$F_{4,76} = 1.21$	$F_{4,76} = 0.70$
Vm	$F_{4,76} = 1.01$	$F_{4,76} = 1.71$	$F_{4,76} = 0.56$	$F_{4,76} = 0.50$	$F_{4,76} = 1.47$	$F_{4,76} = 1.51$	$F_{4,76} = 1.08$	$F_{4,76} = 0.41$
Vxm	$F_{4,76} = 0.88$	$F_{4,76} = 1.67$	$F_{4,76} = 1.65$	$F_{4,76} = 0.77$	$F_{4,76} = 1.37$	$F_{4,76} = 1.72$	$F_{4,76} = 0.91$	$F_{4,76} = 0.43$
Vym	$F_{4,76} = 1.09$	$F_{4,76} = 1.19$	$F_{4,76} = 0.67$	$F_{4,76} = 0.29$	$F_{4,76} = 1.31$	$F_{4,76} = 1.23$	$F_{4,76} = 1.22$	$F_{4,76} = 0.80$
Ay	$F_{4,76} = 0.83$	$F_{4,76} = 1.35$	$F_{4,76} = 1.00$	$F_{4,76} = 1.55$	$F_{4,76} = 3.19$ *	$F_{4,76} = 0.72$	$F_{4,76} = 0.79$	$F_{4,76} = 2.28$

Postural Sway Parameter	Sex * Vision * Sound * Neck F/E	Vision * Neck Rotation * Neck F/E	Sex * Vision * Neck Rotation * Neck F/E	Sound * Neck Rotation * Neck F/E	Sex * Sound * Neck Rotation * Neck F/E	Vision * Sound * Neck Rotation * Neck F/E	Sex * Vision * Sound * Neck Rotation * Neck F/E
X	$F_{4,76} = 1.54$	$F_{4,76} = 0.80$	$F_{4,76} = 0.37$	$F_{8,152} = 1.87$	$F_{8,152} = 0.40$	$F_{8,152} = 1.98$	$F_{8,152} = 0.52$
Y	$F_{4,76} = 0.33$	$F_{4,76} = 0.84$	$F_{4,76} = 0.20$	$F_{8,152} = 3.39$ **	$F_{8,152} = 0.85$	$F_{8,152} = 1.18$	$F_{8,152} = 2.21$ *
Sx	$F_{4,76} = 1.36$	$F_{4,76} = 0.12$	$F_{4,76} = 1.03$	$F_{8,152} = 0.72$	$F_{8,152} = 1.44$	$F_{8,152} = 1.61$	$F_{8,152} = 0.73$
Sr	$F_{4,76} = 1.49$	$F_{4,76} = 0.35$	$F_{4,76} = 0.31$	$F_{8,152} = 0.52$	$F_{8,152} = 1.75$	$F_{8,152} = 1.20$	$F_{8,152} = 0.81$
Sl	$F_{4,76} = 1.03$	$F_{4,76} = 0.45$	$F_{4,76} = 1.11$	$F_{8,152} = 1.23$	$F_{8,152} = 0.73$	$F_{8,152} = 1.08$	$F_{8,152} = 0.73$
Sy	$F_{4,76} = 0.33$	$F_{4,76} = 1.24$	$F_{4,76} = 0.40$	$F_{8,152} = 0.85$	$F_{8,152} = 0.96$	$F_{8,152} = 0.66$	$F_{8,152} = 0.72$
Sa	$F_{4,76} = 0.61$	$F_{4,76} = 1.17$	$F_{4,76} = 0.54$	$F_{8,152} = 0.43$	$F_{8,152} = 1.08$	$F_{8,152} = 0.51$	$F_{8,152} = 0.83$
Sp	$F_{4,76} = 0.32$	$F_{4,76} = 1.57$	$F_{4,76} = 1.55$	$F_{8,152} = 1.43$	$F_{8,152} = 1.57$	$F_{8,152} = 1.83$	$F_{8,152} = 1.41$
TLy	$F_{4,76} = 1.05$	$F_{4,76} = 1.12$	$F_{4,76} = 0.46$	$F_{8,152} = 1.23$	$F_{8,152} = 1.14$	$F_{8,152} = 0.71$	$F_{8,152} = 1.21$
TL	$F_{4,76} = 0.78$	$F_{4,76} = 1.35$	$F_{4,76} = 0.38$	$F_{8,152} = 1.42$	$F_{8,152} = 1.38$	$F_{8,152} = 1.05$	$F_{8,152} = 1.60$
TLx	$F_{4,76} = 1.22$	$F_{4,76} = 0.70$	$F_{4,76} = 0.66$	$F_{8,152} = 0.98$	$F_{8,152} = 0.78$	$F_{8,152} = 0.48$	$F_{8,152} = 0.86$
Vym	$F_{4,76} = 1.03$	$F_{4,76} = 1.18$	$F_{4,76} = 0.50$	$F_{8,152} = 1.27$	$F_{8,152} = 1.18$	$F_{8,152} = 0.67$	$F_{8,152} = 1.16$
Vm	$F_{4,76} = 0.94$	$F_{4,76} = 1.32$	$F_{4,76} = 0.39$	$F_{8,152} = 1.85$	$F_{8,152} = 1.44$	$F_{8,152} = 0.88$	$F_{8,152} = 1.33$
Vxm	$F_{4,76} = 1.18$	$F_{4,76} = 0.72$	$F_{4,76} = 0.69$	$F_{8,152} = 1.01$	$F_{8,152} = 0.82$	$F_{8,152} = 0.46$	$F_{8,152} = 0.83$
Ay	$F_{4,76} = 1.62$	$F_{4,76} = 1.89$	$F_{4,76} = 0.81$	$F_{8,152} = 2.33$ *	$F_{8,152} = 1.10$	$F_{8,152} = 1.91$	$F_{8,152} = 0.41$

* $p<0.05$, ** $p<0.01$ significant influence on each variable or combination of variables on each postural sway parameter.

Table A11.1 The influence of sex, vision, sound, neck rotation and neck flexion/extension and their interaction on the various parameters of postural sway behaviour.

Appendix 12: Analyses of variance for Chapter 11.

Postural Sway Parameter	Sex	Sound	Sex * Sound	Velocity of Head Movement (Velocity)	Sex * Velocity	Direction of Head Movement (Direction)	Sex * Direction	Sound * Velocity
X	$F_{1,20} = 6.47$ *	$F_{2,40} = 0.55$	$F_{2,40} = 0.19$	$F_{1,20} = 1.07$	$F_{1,20} = 2.18$	$F_{7,140} = 1.02$	$F_{7,140} = 0.32$	$F_{2,40} = 1.26$
Y	$F_{1,20} = 0.03$	$F_{2,40} = 0.21$	$F_{2,40} = 0.99$	$F_{1,20} = 4.01$	$F_{1,20} = 2.07$	$F_{7,140} = 4.95$ **	$F_{7,140} = 0.93$	$F_{2,40} = 0.27$
Sx	$F_{1,20} = 0.14$	$F_{2,40} = 22.42$ **	$F_{2,40} = 0.11$	$F_{1,20} = 31.56$ **	$F_{1,20} = 1.06$	$F_{7,140} = 3.96$ **	$F_{7,140} = 0.55$	$F_{2,40} = 12.50$ **
Sr	$F_{1,20} = 0.09$	$F_{2,40} = 20.40$ **	$F_{2,40} = 0.11$	$F_{1,20} = 37.16$ **	$F_{1,20} = 0.85$	$F_{7,140} = 3.77$ **	$F_{7,140} = 0.53$	$F_{2,40} = 13.16$ **
Sl	$F_{1,20} = 0.21$	$F_{2,40} = 23.08$ **	$F_{2,40} = 0.11$	$F_{1,20} = 25.41$ **	$F_{1,20} = 1.18$	$F_{7,140} = 3.63$ **	$F_{7,140} = 0.61$	$F_{2,40} = 10.35$ **
Sy	$F_{1,20} = 0.64$	$F_{2,40} = 15.71$ **	$F_{2,40} = 0.07$	$F_{1,20} = 100.52$ **	$F_{1,20} = 2.33$	$F_{7,140} = 13.80$ **	$F_{7,140} = 0.23$	$F_{2,40} = 19.35$ **
Sa	$F_{1,20} = 0.72$	$F_{2,40} = 16.76$ **	$F_{2,40} = 0.13$	$F_{1,20} = 114.29$ **	$F_{1,20} = 1.63$	$F_{7,140} = 14.01$ **	$F_{7,140} = 0.16$	$F_{2,40} = 13.31$ **
Sp	$F_{1,20} = 0.55$	$F_{2,40} = 13.37$ **	$F_{2,40} = 0.25$	$F_{1,20} = 67.43$ **	$F_{1,20} = 2.33$	$F_{7,140} = 11.11$ **	$F_{7,140} = 0.32$	$F_{2,40} = 21.93$ **
TL	$F_{1,20} = 0.24$	$F_{2,40} = 17.28$ **	$F_{2,40} = 0.37$	$F_{1,20} = 41.60$ **	$F_{1,20} = 1.39$	$F_{7,140} = 4.85$ **	$F_{7,140} = 0.69$	$F_{2,40} = 2.87$
TLx	$F_{1,20} = 0.26$	$F_{2,40} = 13.93$ **	$F_{2,40} = 0.34$	$F_{1,20} = 25.94$ **	$F_{1,20} = 1.11$	$F_{7,140} = 14.75$ **	$F_{7,140} = 1.17$	$F_{2,40} = 6.11$ **
TLy	$F_{1,20} = 0.27$	$F_{2,40} = 13.82$ **	$F_{2,40} = 0.46$	$F_{1,20} = 53.19$ **	$F_{1,20} = 1.34$	$F_{7,140} = 8.05$ **	$F_{7,140} = 0.32$	$F_{2,40} = 055$
Vm	$F_{1,20} = 0.24$	$F_{2,40} = 17.28$ **	$F_{2,40} = 0.37$	$F_{1,20} = 41.60$ **	$F_{1,20} = 1.39$	$F_{7,140} = 4.85$ **	$F_{7,140} = 0.69$	F2,40 = 2.87
Vxm	$F_{1,20} = 0.26$	$F_{2,40} = 13.93$ **	$F_{2,40} = 0.34$	$F_{1,20} = 25.94$ **	$F_{1,20} = 1.11$	$F_{7,140} = 4.75$ **	$F_{7,140} = 1.17$	$F_{2,40} = 6.11$ **
Vym	$F_{1,20} = 0.27$	$F_{2,40} = 13.82$ **	$F_{2,40} = 0.46$	$F_{1,20} = 53.19$ **	$F_{1,20} = 1.34$	$F_{7,140} = 8.05$ **	$F_{7,140} = 0.32$	$F_{2,40} = 0.55$
Ay	$F_{1,20} = 0.06$	$F_{2,40} = 6.98$ **	$F_{2,40} = 0.38$	$F_{1,20} = 5.59$ *	$F_{1,20} = 0.00$	$F_{7,140} = 1.61$	$F_{7,140} = 0.61$	$F_{2,40} = 1.28$

Postural Sway Parameter	Sex * Sound * Velocity	Sound * Direction	Sex * Sound * Direction	Velocity * Direction	Sex * Velocity * Direction	Sound * Velocity * Direction	Sex * Sound * Velocity * Direction
X	$F_{2,40} = 0.67$	$F_{14,280} = 1.19$	$F_{14,280} = 1.04$	$F_{7,140} = 0.84$	$F_{7,140} = 0.70$	$F_{14,280} = 0.96$	$F_{14,280} = 0.68$
Y	$F_{2,40} = 3.02$	$F_{14,280} = 1.79$ *	$F_{14,280} = 1.44$	$F_{7,140} = 0.96$	$F_{7,140} = 0.28$	$F_{14,280} = 0.64$	$F_{14,280} = 0.46$
Sx	$F_{2,40} = 0.02$	$F_{14,280} = 2.79$ **	$F_{14,280} = 0.95$	$F_{7,140} = 1.39$	$F_{7,140} = 1.18$	$F_{14,280} = 2.41$ **	$F_{14,280} = 0.63$
Sr	$F_{2,40} = 0.03$	$F_{14,280} = 2.55$ **	$F_{14,280} = 0.67$	$F_{7,140} = 1.35$	$F_{7,140} = 1.11$	$F_{14,280} = 2.52$ **	$F_{14,280} = 0.44$
Sl	$F_{2,40} = 0.15$	$F_{14,280} = 2.62$ **	$F_{14,280} = 1.16$	$F_{7,140} = 1.15$	$F_{7,140} = 0.99$	$F_{14,280} = 1.93$ *	$F_{14,280} = 0.83$
Sy	$F_{2,40} = 0.48$	$F_{14,280} = 2.09$ *	$F_{14,280} = 1.26$	$F_{7,140} = 10.35$ **	$F_{7,140} = 0.98$	$F_{14,280} = 0.95$	$F_{14,280} = 0.89$
Sa	$F_{2,40} = 0.22$	$F_{14,280} = 2.03$ *	$F_{14,280} = 1.68$	$F_{7,140} = 8.95$ **	$F_{7,140} = 0.78$	$F_{14,280} = 1.32$	$F_{14,280} = 1.22$
Sp	$F_{2,40} = 0.73$	$F_{14,280} = 1.72$	$F_{14,280} = 0.78$	$F_{7,140} = 7.28$ **	$F_{7,140} = 1.59$	$F_{14,280} = 0.77$	$F_{14,280} = 0.59$
TL	$F_{2,40} = 1.18$	$F_{14,280} = 3.76$ **	$F_{14,280} = 0.88$	$F_{7,140} = 1.93$	$F_{7,140} = 0.99$	$F_{14,280} = 2.49$ **	$F_{14,280} = 0.74$
TLx	$F_{2,40} = 2.41$	$F_{14,280} = 2.99$ **	$F_{14,280} = 1.02$	$F_{7,140} = 0.84$	$F_{7,140} = 0.66$	$F_{14,280} = 2.21$**	$F_{14,280} = 0.91$
TLy	$F_{2,40} = 0.37$	$F_{14,280} = 4.01$ **	$F_{14,280} = 0.78$	$F_{7,140} = 6.25$ **	$F_{7,140} = 1.60$	$F_{14,280} = 2.02$ *	$F_{14,280} = 0.46$
Vm	$F_{2,40} = 0.18$	$F_{14,280} = 3.76$ **	$F_{14,280} = 0.88$	$F_{7,140} = 1.93$	$F_{7,140} = 0.99$	$F_{14,280} = 2.49$ **	$F_{14,280} = 0.74$
Vxm	$F_{2,40} = 2.41$	$F_{14,280} = 2.99$ **	$F_{14,280} = 1.02$	$F_{7,140} = 0.84$	$F_{7,140} = 0.66$	$F_{14,280} = 2.21$ **	$F_{14,280} = 0.91$
Vym	$F_{2,40} = 0.37$	$F_{14,280} = 4.01$ **	$F_{14,280} = 0.78$	$F_{7,140} = 6.25$ **	$F_{7,140} = 1.60$	$F_{14,280} = 2.02$ *	$F_{14,280} = 0.46$
Ay	$F_{2,40} = 2.63$	$F_{14,280} = 0.93$	$F_{14,280} = 1.04$	$F_{7,140} = 0.67$	$F_{7,140} = 1.45$	$F_{14,280} = 0.90$	$F_{14,280} = 0.98$

* $p<0.05$, ** $p<0.01$ significant influence on each variable or combination of variables on each postural sway parameter.

Table A12.1 The influence of sex, sound, velocity and direction of head movement and their interaction on the various parameters of postural sway behaviour.