The Effect of Old Age on Motor Control: Performance and Learning

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The candidate confirms that the work submitted is his/her own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Publications

Three of the experiments that have been completed as part of this doctoral research have been published as journal articles. A further five experiments have been submitted and are presently under review. The publications are listed below with a full reference, brief description of the content, and an indication of the study's location within this thesis. In the case of all publications listed, the candidate was responsible for the production of the content, with named authors providing support through review and modification only.

Raw, R. K., Kountouriotis, G. K., Mon-Williams, M., & Wilkie, R. M. (2012). Movement control in older adults: does old age mean middle of the road? *Journal of Experimental Psychology: Human Perception and Performance,* 38(3), 735-745.
This paper examines age differences in the spatial and temporal parameters of movement using two different tasks. In the first experiment, participants manually traced paths using a handheld stylus – this study forms a large portion of **Chapter 2** of this thesis. In the second experiment, participants steered along roads in a simulated driving environment – this study forms a large portion of **Chapter 3** of this thesis. Conclusions drawn suggest that older adults are sensitive to their level of motor performance and make compensatory adjustments to their movement in order to meet task demands.

Raw, R. K., Wilkie, R., Culmer, P., & Mon-Williams, M. (2012). Reduced motor asymmetry in older adults tracing paths. *Experimental Brain Research*, 217(1), 35-41.
This paper investigated age differences in manual asymmetries using a task that required participants to trace paths of variable thickness using their preferred (right) and non-preferred (left) hand. The experiment in this paper

forms a large portion of **Chapter 4** of this thesis, and highlights interesting issues regarding age-related changes in hemispheric lateralisation.

Raw, R. K., Wilkie, R., Sutherland, E., Williams, J. H. G., & Mon-Williams, M. (submitted). Getting the measure of manual asymmetries in older adults. *Journal of Experimental Psychology: Human Perception and Performance.*

This paper continues on from previous work concerning age differences in manual asymmetries (see Raw et al., 2012 and **Chapter 4**). Two experiments were designed to compare preferred (right) and non-preferred (left) hand performance across a range of manual control tasks (e.g. tracing, tracking, aiming), with results suggesting that manual asymmetries are largely influenced by task design. This paper features in **Chapter 5** of the thesis.

Raw, R. K., Allen, R.,* Williams, J. H. G., *Mon-Williams, M., & Wilkie, R. (submitted). Novel movement pattern acquisition as a function of age and hand: Does better performance mean better learning*? *Journal of Experimental Psychology: General.

This paper includes three experiments that examined whether poor motor ability (as indexed by shorter movement duration) negatively affects motor sequence learning. Experiment one found reduced movement durations in older adults during a basic aiming task, and experiment two also identified reduced motor sequence learning in the older group. The final experiment varied motor performance within-subjects by comparing sequence learning between the preferred (right) and non-preferred (left) hand. As both age groups were found to be worse at sequence learning when using their non-preferred (i.e. slower) hand, the paper concluded that reduced motor performance can impact negatively on the processes necessary for learning new motor sequences. These experiments feature in **Chapter 6** of the thesis.

Contributions to Conference Volumes

Four of the experiments completed as part of this doctorate have been presented in poster-format at conferences. The abstracts for this work have also been published. The full abstract reference is provided below with a brief description of the contents, an indication of the study's location within the thesis and a statement of the responsibilities assigned to listed authors.

Raw, R. K., Wilkie, & Mon-Williams, M. Perception and Action in older adults: evidence of reduced motor asymmetry. *AVA,* North America, Nov 2011.

This poster reported the results of experiments detailed in **Chapter 5** of the thesis. The research is concerned with age differences in manual asymmetries and the problems that can arise when trying to capture subtle differences in performance between the preferred and non-preferred hands. The doctoral candidate presented the abstract as a poster and was responsible for the production of the content, with named authors providing support through review and modification only.

Wilkie, R. M., Raw, R. K., Kountouriotis, G. K., & Mon-Williams. Age differences negotiating paths of different widths at different speeds: does old age mean "middle of the road"? *Vision Sciences Society Annual Conference*, 257-256, May 2011.

This poster presented data from experiments that are reported in **Chapters 2** and **Chapter 3** of this thesis, whereby age differences in spatial and temporal compensation were examined using two different motor tasks (tracing and driving). **Dr. Richard Wilkie** assisted with formatting of the abstract into poster-format and presented it at the conference on behalf of the candidate. The candidate was responsible for the production of the content. The remaining named authors provided support through review and modification.

Acknowledgements

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“For I can do all things through Christ, who gives me strength.”

Philippians 4:13

Abstract

A decrease in motor ability can have a profound impact on a person's capacity to maintain independence. Motor skill levels decline with age and this can create difficulties for older adults as they attempt to maintain independent lives. The fact that people in today's society are living for much longer means that robust methods for examining movement in older adults, must be developed. These methods will increase our understanding of *how* movement deteriorates with age and *inform* approaches to rehabilitation in cases where movement is lost (e.g. motor paresis after stroke).

Accordingly, this doctoral research used sophisticated kinematic technology to create a series of computerised visuomotor tasks designed to achieve the following **primary aims** (i) to examine specific questions regarding age differences in motor performance; (ii) to create an experimental task to measure and infer potential causes of age-related changes in motor learning; and (iii) use the motor learning task to assess the outcomes of tDCS in healthy younger and older adults. A **secondary aim** was to produce tests that have the potential for use in rehabilitative settings, where more sensitive methods of assessment are required.

Chapter 1 reviews previous research on the topics of ageing, motor control, and rehabilitation, and identifies needs for further empirical investigation. Age differences in motor performance are examined in the experimental work of **Chapters 2** and **3,** which suggests that older people compensate for motor decline by making spatial and temporal adjustments to their movements in order to meet task demands – a finding that generalised between two different motor tasks. **Chapter 4** considers performance differences between the preferred and non-preferred hand, and includes findings of a tracing study where manual asymmetries were reduced in older adults. The problems that can arise when measuring differences between

the hands are, however, highlighted in the experimental work of **Chapter 5**. The research in **Chapters 6** and **7** focuses on motor learning. In **Chapter 6** a motor sequence learning task is developed, which was used to examine the relationship between motor performance and learning. This task paradigm was used again in **Chapter 7**, which begins by reviewing previous studies that have applied Transcranial Direct Current Stimulation (tDCS) to modify movement in healthy people and in stroke populations, and ends with two experiments that found no beneficial effects of tDCS on motor sequence learning in younger and older adults. Finally, **Chapter 8** summarises the findings of each experimental chapter and considers future applications of the motor tasks designed throughout this doctoral work.

Glossary

A number of abbreviations and acronyms are used throughout this thesis. Although these are explained alongside their first instance in the text, they are listed here for ease of reference:

ADLs	Activities of Daily Living
ACE-R	Addenbrooke's Cognitive Examination (Revised)
aSAH	Aneurysmal Subarachnoid Hemorrhage
AS	Anodal Transcranial Direct Current Stimulation (tDCS)
BBT	Box and Block Test
BOLD fMRI	Blood Oxygen Level-Dependent fMRI
CIMT	Constraint Induced Movement Therapy
CNS	Central Nervous System
CR	Number of moves recalled in the correct sequential order
CS	Cathodal Transcranial Direct Current Stimulation (tDCS)
DCD	Developmental Coordination Disorder
DCs	Direct Currents
DLPFC	Dorsolateral Prefrontal Cortex
EHI	Edinburgh Handedness Inventory
fMRI	Functional Magnetic Resonance Imaging
HAROLD	Hemispheric Asymmetry Reduction in Older Adults
IADLs	Instrumental Activities of Daily Living
JTT	Jebsen Taylor Hand Function Test
KineLab	Kinematic Assessment Tool
M1	Primary Motor Cortex

MEP Motor Evoked Potential

MHQ Medical Health Questionnaire

MIS Minimally Invasive Surgery

MT Movement Time

MT_r Recall Movement Time

MT_t Training Movement Time

NIBS Non-Invasive Brain Stimulation

OT Occupational Therapy

PET Positron Emission Tomography

PFC Prefrontal Cortex

PL Path Length

PM Premotor Cortex

PNS Peripheral Nerve Stimulation

pre-SMA Presupplementary Motor Area

rCBF Regional Cerebral Blood Flow

RCT Randomised Controlled Trial

RMSE Root Mean Square Error

RT Reaction Time

rTMS Repetitive Transcranial Magnetic Stimulation

SA Shape Accuracy

SACF Speed Accuracy Cost Function

SMA Supplementary Motor Area

SRT Serial Reaction Time Task

SVIPT Sequential Visual Isometric Pinch Task

tDCS Transcranial Direct Current Stimulation

TMS Transcranial Magnetic Stimulation

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Chapter 1
Introduction

If hand function is impaired, '*the drink will be spilled, the food will make a mess, and the pen will leave a poorly discernible scribble on the paper*' (Shim, Brendan, Vladimir & Latash, 2004, p.221). Precise control over the hands and fingers is integral to most everyday activities of daily living. In our youth and middle-age, such activities can be achieved swiftly, accurately and often unconsciously. Old age, however, brings about changes that can result in significant motor decline. Some of these changes are inevitable physiological changes – when the motor system ages there is a loss in sensory sensitivity, the muscles weaken, and the joints are no longer as flexible (Barnet & Cobbold, 1968; Campbell, McComas, & Petito, 1973; Delbono, 2003; Faulkner, Larkin, Claflin & Brooks, 2007; Clark & Taylor, 2012). Older adults are also more susceptible to diseases that directly affect the motor system (e.g. stroke).

The impact of age-related motor decline is profound. Reduced hand function at the onset of older age predicts decreased hand strength and greater difficulties when completing simple motor tasks many years later (Rantenen, Guralnik & Foley et al., 1999; Giampaoli, Ferrucci & Cecchi et al., 1999). This includes difficulties encountered when carrying out basic Activities of Daily Living (ADLs; Katz, Ford & Moskowitz et al., 1963) such as bathing or dressing, and Instrumental Activities of Daily Living (IADLs; Lawton & Brody, 1969) that are essential for independent living (e.g. shopping, making a phone call, and doing the laundry). Furthermore, in cases where disease disrupts and/or damages the motor system, movement can be lost entirely (e.g. motor paresis following stroke; American Heart Association, 2008).

So what can be done to improve motor control in the older population? It is not possible to answer this question without a greater understanding of exactly *how* movement is affected both by 'healthy' ageing and by disease. Moreover, with life expectancy in the United Kingdom increasing at a rate of around two years per decade (House of Lords Science & Technology Committee, 2005), it is also a question that requires immediate attention. The overriding aim of this doctoral work was to contribute novel findings to the current evidence base regarding the effects of ageing on motor control. This was achieved by developing a range of kinematic visuomotor tasks to compare hand movements in healthy younger and older adults. These tasks were also used to examine whether movement can be enhanced with Transcranial Direct Current Stimulation (tDCS) – a non-invasive brain stimulation (NIBS) technique that has recently been used for the rehabilitation of movement after stroke.

The following sections of the introduction set the background for the experimental chapters (**Chapters 2-7**) and outline the research questions. **Section 1.1** firstly distinguishes between common terms used when studying the motor system and defines the area of motor control that was studied in the present research. An overview of previous findings on the effects of ageing on movement in healthy populations is then provided in **Section 1.2. Section 1.3** follows on to consider rehabilitation, with a specific focus on the rehabilitation of movement following stroke, and the use of tDCS in this context**. Section 1.4** introduces the kinematic assessment tool used to design the motor tasks for the experimental work, and outlines the benefits of using this method when studying movement. Finally, **Section 1.5** summarises the research aims and states how they were met within each experimental chapter.

1.1 Definitions and Research Focus

Before reviewing past literature, it is helpful to consider how movement has been defined in the past as a means of understanding the subcomponents of motor control, and simplifying the communication of findings within such a broad field. Schmidt and Lee (1999, p.416) defined motor control as '*an area* *of study dealing with the understanding of the neural, physical and behavioural aspects of movement*'. The experimental work of this thesis considers predominantly age differences in motor control that can be studied at the behavioural level of analysis but also with some consideration of the neural and physiological aspects. The use of tDCS, for example, involves careful consideration of how movement is controlled at a neural level (see **Section 1.3.2** and **Chapter 7**). An understanding of how ageing affects the motor networks in the brain can also help to explain why older adults perform differently to the young on some motor tasks (see **Section 1.2.1**).

The motor tasks that feature in the experimental chapters of this thesis are essentially tests of *motor coordination*; they measure how well two or more joints move together swiftly and accurately in order to achieve a specific goal (Schmidt & Lee, 1999; Desrosiers, Hébert, Bravo & Dutil, 1995). Motor cordination therefore underlies our ability to carry out most daily tasks without even thinking about it – pouring a cup of tea, brushing our teeth, buttoning a shirt etc. The tasks used throughout the thesis fall predominantly within the definition of 'fine' (rather than 'gross') motor coordination (according to the classification of Cratty, 1964), as they directy involve (minimal) muscular involvement that is restricted mainly to the wrist and fingers. One exception could perhaps be the virtual reality steering task that features in **Chapter 3**, where larger arm movements were also required, but these movements were still relatively small with little force compared to so-called 'gross motor' tasks such as playing tennis or opening a door.

A second important issue to clarify at the outset of this thesis involves distinguishing between the concepts of '*motor performance'* and '*motor learning*, especially as the two are compared in **Chapter 6**. I will rely upon Schmidt and Vrisberg's (2008, p.11) definitions of these terms whereby (i) **motor performance** is defined as *'the observable production of voluntary action or a motor skill'*, which can be influenced by temporary factors such as mood or fatigue; and where (ii) **motor learning** refers to *'changes, associated with practice or experience, in internal processes that determine a person's capability for producing a motor skill'*. Moreover, because motor learning is an internal state, it is important to note that it cannot be measured directly, but rather is inferred by observing its effects on measures of motor performance (e.g. a comparison of how speed or accuracy changes over time; Tresilian, 2012). With these definitions in mind, the experimental work of **Chapters 2-7** all involved some assessment of age differences in *motor performance*, whereas the studies in **Chapters 6** and **7** specifically focused on examining *motor learning*. For clarity, the term ‘performance’ will hereafter only be used to describe cases where learning was not explicitly considered. This is important in the next section, where two bodies of literature are reviewed – studies that have examined age-related changes in motor performance, and studies that have measured the effects of ageing on motor learning.

1.2 Past Studies in Healthy Populations

The following sections provide an overview of findings from previous research that has considered the effects of ageing on fine motor performance (**Section 1.2.1**) and learning (**Section 1.2.2**), respectively.

1.2.1 Age Differences in Motor Performance

There is a general consensus among studies measuring age-related changes in motor performance that movements become slower, less accurate and more variable with increasing age (Schmidt & Lee, 1999). For example, older people show reduced accuracy in simple writing tasks (Contreras-Vidal, Teulings and Stelmach, 1998), and when making aiming movements (Pratt, Chasteen & Abrams, 1994; Morgan, Phillips & Bradshaw et al., 1994; Seidler Alberts & Stelmach, 2002; Welsh, Higgins & Elliot, 2007; Poston, Van Gemmert, Barduson & Stelmach, 2009). The notion that ageing ‘slows you down’ is also more than just an anecdote – experiments measuring how long it takes participants to complete a movement (i.e. Movement Time; MT) or to react to a stimulus (i.e. Reaction Time; RT) have found that older participants are slower than younger individuals (Welford, Norris & Shock, 1969: Warabi, Noda & Kato, 1986; Stelmach, Amrhein &

Goggin, 1988; Goggin & Stelmach, 1990; Jagacinski, Liao & Fayyad, 1995; Smith, Umberger & Manning et al., 1999; Poston et al., 2009; Bautmans, Vantieghem, & Gorus et al., 2011). Longitudinal research has even demonstrated the gradual increase of motor slowing across time, an effect that is unsurprisingly exacerbated by task complexity (i.e. more complicated versions of RT tasks lead to even slower responses in older adults; Fozard, Vercruyssen & Reynolds et al., 1994).

Another approach to measuring age differences in fine motor coordination has been to look at less constrained tasks where the participant can adjust the speed and accuracy of their performance. This literature consistently demonstrates reduced overall performance in older groups. For example, Verkerk, Schouten and Oosterhuis (1990) used both the Nail test and Spiral test, and found older participants performed less well than younger participants (i.e. scored lower) in both cases – the Nail Test entails moving nails in a specific order from one side of a board to the other within a 30s timeframe, and the Spiral Test requires participants to trace around a spiral without touching or venturing outside the spiral boundaries as quickly as possible (i.e. and there is a time penalty for crossing the boundary). Another common test for assessing motor coordination (especially in the clinical environment) is the Finger-Nose Test. In this test, participants repeatedly touch the index finger back-and-forth between the nose and a target. Again, older adults have been found to achieve fewer accurate nose-to-target movements within a given set time frame (Desrosiers, Hérbert, Bravo & Dutil, 1995). One limitation of this research is that because these tasks rely upon a single measure of performance that is a composite of speed and accuracy, it is hard to draw firm conclusions about whether there are independent effects of ageing upon the components (discussed further in **Section 1.2.1.1**).

A final observation that appears prominently in the ageing and movement literature concerns age-related changes in the variability of motor performance (Krampe, 2002). One way of examining variability is to measure ‘jerk’, which captures fluctuations in the acceleration of a given movement (to be precise, jerk is the derivative of acceleration). Jerk has therefore been used as a measure of ‘smoothness’ or ‘fluency’, and older adults are found to produce higher (i.e. jerkier) scores than their younger counterparts (Cook, Brown & Cunningham, 1989; Darling, Cooke & Brown, 1989; Contras-Vidal et al., 1998). This increase in movement variability could be caused by degradation to the neuromuscular system that accompanies increased age. A review by Faulkner et al. (2007) noted that up to 50% of muscle mass is lost between the age of 40 and 80 years, accompanied by a decline in strength and power. A deterioration in neuromuscular control, as a result of death or dysfunction in motor neurons (e.g. Campbell et al., 1973), could therefore explain why older people find it harder to modulate the forces produced by their digits when completing fine motor coordination tasks (e.g. weaker maximum force and increased variability shown on various grip force and pressing tasks; Galganski, Fuglevand & Enoka, 1993; Shinohara, Latash & Zatsiorsky, 2003; Shinohara, Li & Kang et al., 2003; Shinohara, Scholtz, Zatsiorsky & Latash, 2004; Shim, Lay, Zatsiorsky & Latash, 2004; Voelcker-Rehage, & Alberts, 2005; Olafsdottir, Yoshida, Zatsiorsky & Latash, 2007).

In sum, the ability to coordinate the hand and digits in a rapid and precise manner becomes problematic in older age. There is, however, substantial evidence to suggest that older people compensate for motor decline. This will be explored in more depth in the next section.

1.2.1.1 Compensation for Motor Decline

The observation that movements become slower with increasing age may in itself reflect a method of compensation for motor decline. In the past, motor slowing has been attributed to a decrease in the speed at which activities in the Central Nervous System (CNS) take place in order to complete a movement – for example nerve conduction times and information processing (Schmidt and Lee, 1999). A general degradation in neuromuscular factors, such as reduced strength and flexibility in the muscles/limbs (Faulkner et al., 2007) can also limit movement speed. However, while ageing clearly causes a reduction in the speed at which movements can be carried out, because slower movements tend to be more accurate, it is possible that age-related slowing is also driven by compensatory processes. Accordingly, studies that have assessed how ageing affects speed and accuracy as independent markers of performance imply that older adults could be slowing their movements down in order to maintain accuracy (e.g. Welsh et al., 2007).

The relationship between movement speed and accuracy was formally described by Fitts (1954), who argued that the time taken to complete a movement is a function of movement amplitude and target size. The relationship between duration and task parameters has since been examined extensively within the movement literature (see Plamondon & Alimi, 1997 for a comprehensive review) and studies have repeatedly shown that increased accuracy demands (e.g. a decreasing target size in an aiming task) produces a lawful increase in movement duration – the so-called ‘speed-accuracy trade-off’. Because of this trade-off, combined measures of speed and accuracy can be problematic when studying group differences in motor performance, especially in light of the possibility that older people prioritise accuracy over speed.

Compensatory ‘strategic slowing’ has been demonstrated in older participants who have been found to complete a task at a slower rate, but with comparable accuracy to their younger counterparts. Welsh et al. (2007) suggested that older people adopt a ‘play-it-safe’ strategy when aiming since older adults were able to achieve the same level of accuracy as the young (but at a slower pace). Such strategic slowing has also been observed in tracing with older participants requiring more time than the young to trace between targets (Morgan et al., 1994).

An important issue that arises from the previous observations is how a strategic reduction in movement speed might benefit older people. Evidence suggests that humans are able to rapidly assess their intrinsic motor variability and optimize their motor strategies (Trommershäuser, Gepshtein, Maloney, Landy & Banks, 2005). The strategy of generating slower actions can specifically make it easier for online feedback to be used to control and correct movements during execution. In the past, the preparation phase of movement has been assessed by recording the time taken to initiate movement (i.e. RT). For example, in Warabi, Noda and Kato's (1986) study, increased RT's in an aiming task suggested that older adults spent more time in the initial (i.e. ‘open-loop’) preparatory phase of movement. Furthermore, older adults demonstrated longer total movement durations (i.e. MTs), suggesting that more time was also spent in the error-correcting (i.e. ‘closed-loop’) phase of movement where visual feedback (which older adults are particularly depend upon; Haaland, Harrington & Grice, 1993), can be used to make a series of ‘online’ adjustments (i.e. during the task). Likewise, Pohl, Winstein & Fisher (1996) found that older adults made a greater number of corrective adjustments during a continuous tapping task, which was also paired with longer adjustment times relative to the young.

It seems that motor slowing is a strategy that can allow older adults to perform at an equivalent level of spatial accuracy to the young, with decrements only becoming apparent when there is an external timing constraint imposed upon the task (Morgan et al., 1994; Welsh et al., 2007). This means that there are two possible interpretations of an increase in movement duration as a function of age; it could be (i) a direct consequence of age-related physiological changes, or (ii) a strategic response to these changes. Strategic compensation does not necessarily mean that behaviour is adjusted through conscious control. Older adults may consciously attempt to compensate for their difficulties and/or adapt to increased signal variability in a cognitively impenetrable manner (Desrosiers et al., 1995; Krampe, 2002; Smith, Umberger & Manning et al., 1999; Verkerk et al., 1990).

The effects of ageing on the temporal and spatial adjustments made when completing motor coordination tasks is a topic that is further explored in **Chapters 2** and **3** of this thesis. The suggestion that older adults are sensitive to their own level of motor performance and are capable of adjusting their motor strategy accordingly is a particularly important observation to address empirically, as findings can be informative in a rehabilitative setting. For example, if a clinician advises a patient to increase his/her speed; it could potentially interfere with the patient’s successful method of strategic compensation. Moreover, this area of research is highly relevant to issues relating to the process of healthy ageing. An example of this can be found in **Chapter 3,** where experimental findings are discussed with reference to the topic of road safety in older drivers.

1.2.1.2 Manual Asymmetries

The literature reviewed so far has focused on age-related changes in performance when examining movement of the *preferred* hand. The term 'handedness' refers to one's preference towards using either the left or right hand when carrying out skilled motor tasks. The majority of the population demonstrate a hand preference and show better performance when completing motor tasks with their preferred hand. There are two main benefits of considering the effects of ageing on the natural asymmetries typically observed between the preferred and non-preferred hand; (i) findings can be informative in a rehabilitative context (e.g. training the non-preferred hand might be more beneficial than commonly presumed); and (ii) results may provide insight into the compensatory processes of the ageing brain. For the purposes of this thesis, all of the experiments were conducted with right-handed participants, as there have been both cognitive and motoric differences associated with hand preference in the past (Kilshaw & Marian, 1983; Nettle, 2003). Specifically, **Chapter 4** examines the theory that manual asymmetries decline in older age as a result of changes in hemispheric lateralisation, and that this may serve a compensatory purpose. Nevertheless, the studies reported in **Chapter 5** highlight difficulties that can arise when trying to measure differences in performance between the two hands.

Handedness is typically established in early childhood and is presumed to be maintained throughout life (Goble & Brown, 2008), hence studies with both children and younger adults have demonstrated the presence of manual asymmetries in the past (e.g. Fagard, 1987; Truman & Hammond, 1990; Culmer, Levesley, Mon-Williams & Williams, 1999). Evidence of manual asymmetries in older populations, however, is less consistent. The fact that older adults have lived more years to practice with the preferred hand makes it reasonable to predict that they might show greater asymmetries, perhaps even more so than the young. On the other hand, ageing is also associated with reduced movement speed and accuracy (**Section 1.2.1**), a decline that could potentially alter their propensity towards the asymmetries seen in younger adulthood.

At the neurological level, motor asymmetry can be explained by lateralisation of brain function, whereby one hemisphere is found to be predominant in a specific function. However, the neural plasticity of the brain means that cortical properties continue to change throughout life and particularly as a consequence of healthy ageing. The ageing brain shows signs of structural change (e.g. atrophy in grey and white brain matter), which in some cases has been associated with reduced motor performance in older adults (see Seidler, Bernard & Burutolu et al., 2010 for a review). More interestingly there is also evidence of age-related functional changes in the brain (Burke & Barnes, 2006; Seidler, Bernard & Burutolu et al., 2010). Specifically, activations in the ageing brain tend to be more widespread, and recent evidence implies an age-related reduction in hemispheric lateralisation, particularly in prefrontal brain regions during cognitive processes. This phenomenon has been labelled by Cabeza and colleagues (e.g. 2002) as 'HAROLD' (Hemispheric Asymmetry Reduction in Older Adults), a model based on neurophysiological studies that find reduced asymmetry between dominant and non-dominant hemisphere activation when older adults complete cognitive tasks (e.g. episodic and semantic memory encoding and retrieval, and inhibitory response). For example, during episodic memory encoding and retrieval, increased prefrontal cortex (PFC) activity is observed in the left hemisphere during encoding and in the right hemisphere during recall in the younger population; whereas in older groups there is a greater bilateral pattern of activation throughout both parts of the task (e.g. Cabeza, Grady & Nyberg et al., 1997). Bilateral patterns of activation are associated with better performance in the old, which suggests that HAROLD may be a compensatory mechanism (Cabeza, Anderson, Locantore & McIntosh, 2002).

If reduced asymmetry of function is evident for a range of different cognitive processes (i.e. if HAROLD is not task-specific), it is likely that HAROLD may also apply to other brain regions. This might include lower-level sensory-motor processes that occur outside of the PFC. In line with this, functional imaging research has indicated an age-related reduction in lateralisation in the temporal and parietal areas (Grady, Bernstein, Beig & Siegenthaler, 2002). Studies in the motor domain also show that activations are more widespread, and additional brain regions are recruited (relative to the young), when older adults perform basic motor tasks such as finger-tapping and button-pressing (Sailer, Dichgans & Gerloff, 2000; Calautti, Serrati & Baron, 2001; Mattay, Fera & Tessitore et al., 2002; Ward & Frackowiak, 2003; Heuninckx, Wenderoth & Debaere et al., 2005; Naccarato, Calautti & Jones et al., 2006; Heuninckx, Wenderoth & Swinnen, 2008).

For clarity, one study measured brain activity using Blood Oxygen-Level Dependent (BOLD) Functional Magnetic Resonance Imaging (fMRI) while participants completed a simple button pressing task. Figure 1.1 overleaf shows subsequent images reproduced from Mattay et al. (2002), where increased levels of activation were identified in the contralateral sensorimotor cortex, lateral premotor cortex (PM), supplementary motor area (SMA), and ipsilateral cerebellum of older adults. Further areas that were not activated in the younger participants, but were in the older group, also included the ipsilateral sensorimotor cortex, putamen and contralateral cerebellum. Interestingly, greater levels of activation in the old were also associated with reduced RTs on the motor task. This suggests that by recruiting additional brain regions, older adults were able to respond more quickly than those in the old group who did not show the same compensatory activations.

Figure 1.1 *Images reproduced from Mattay et al. (2002) showing age differences in brain activation (measured by BOLD fMRI) during a button-pressing task completed with the preferred (right) hand.* ***(A)*** *Younger adults (mean age = 30yrs)* ***(B)*** *Older adults (mean age = 59yrs).*

Similarly, the notion of HAROLD serving some compensatory purpose was suggested by Heuninckx et al., (2008), who found a positive correlation between performance on an interlimb coordination task and bilateral motor cortical activation in older adults – the greater the extent of activation, the better the performance, especially in the more demanding task condition (i.e. moving the hand and foot in opposite directions, rather than in the same direction). The fact that the poorly performing older adults showed similar BOLD signals to those in the younger group, while those with enhanced activations sometimes met the level of performance seen in the young, implies that these differences were of a compensatory nature.

One explanation for the more diffuse pattern of activation in the ageing brain is that transcallosal inhibition, which usually ensures ipsilateral deactivation of primary motor cortex in the young, may be reduced in older people (Ward & Frackowiak 2003; Peinemann, Lehner, Conrad & Sibner, 2001). However, reduced lateralisation is not always found in older groups, and instead seems to vary across different motor tasks. For example, both motor sequence learning (Daselaar, Rombouts, & Veltman et al., 2003) and cued simple movements (Fang, Li & Lu et al., 2005) do not appear to exhibit age-related cortical reorganisation. A similar conflict in findings is also apparent in studies that have examined age-related changes in motor cortical lateralisation at the behavioural level. At present, there are only a few studies that have examined the effects of age on manual asymmetries during skilled behavioural tasks, and not all cases have identified age differences.

One skilled action that has been examined previously is the efficiency of reaching movements, where there do appear to be reduced asymmetries in older adults (Przybyla, Haaland, Bagesteiro & Sainburg, 2011). The coordination of reaching movements is usually superior in the preferred arm (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2002). However, Przybyla et al. (2011) found that in older adults these asymmetries were reduced. One possibility is that ageing leads to reduced asymmetries simply because of a greater impairment to the most skilled (preferred) hand. The results showed, however, that young participants tended to overshoot leftwards of the target when using their non-preferred hand, the older participants produced straighter trajectories that were similar to those shown by the preferred hand (in both age groups). Furthermore, there was no difference in accuracy between the arms in the older group, whereas the young were more accurate when using their preferred arm. Another particularly elegant study has also investigated visuomotor adaptation during reaching movements, and found that older adults showed a similar degree of interlimb transfer after adaptation for both left and right arms, whereas adaptation mainly occurred between the preferred to non-preferred arm in the young (Wang, Przybyla & Wuebbenhorst et al., 2011). Such reduced asymmetries would support the idea that interhemispheric inhibition declines with increased age.

While the latter studies imply HAROLD occurs in the motor domain, there are, conversely, an equal number of studies that report the opposite outcome. Some experiments have found no age differences in manual asymmetries (e.g. Mitrushina, Fogel & D’Elia et al., 1995; Chua, Pollock & Elliot et al., 1995; Francis & Spirduso, 2000; Teixeria, 2008), and others actually report increased asymmetries in older adults compared to the young (e.g. Goldstein & Shelly, 1981; Weller & Latimer-Sayer, 1985; Dolcos, Rice & Cabeza et al., 2002; Chua et al., 1995; Teixeria, 2008). Such variability across studies strongly suggests that the 'HAROLD' phenomenon is not something that can be generalised to all motor behaviour.

An alternative explanation for the conflict within the behavioural literature might be that manual asymmetries are much more subtle than widely presumed, and hence depend largely on the underlying characteristics of the task chosen to measure motor performance. Structural learning theory (e.g. Braun, Waldert & Aersteen & Mehring, 2009) for example, argues that the nervous system acquires general rules that can be readily applied when controlling similar actions, such as in the case of completing an action with the right versus the left hand. Accordingly, asymmetries may only become apparent when participants are pushed to the very limits of their performance capacity, a threshold which will inevitably vary both between individuals and groups. If the task is too difficult then it will be hard to differentiate the preferred and non-preferred hands (i.e. both hands will perform poorly). If the task is not difficult enough, performance in both hands will hit ceiling level. Another vital aspect to consider here is metric choice. Relying solely on one outcome measure, or a combined speed-accuracy measure, for example (e.g. Francis & Spirduso, 2000; Chua et al., 1995; Weller & Latimer-Sayer, 1985; Goldstein & Shelly, 1981; Mitrushina et al., 1995; Mattay et al, 2002) could cause a task to miss asymmetries that manifest in another aspect of performance. The role of task design and metric choice in the study of manual asymmetries is clearly an important issue that requires further empirical investigation. These topics are therefore explored in more detail in **Chapters 4** and **5** of this thesis.

1.2.2 Age Differences in Motor Learning

The previous section of this chapter established unequivocally that old age leads to a decline in motor performance. But does this also mean that older adults find it difficult to learn new motor skills? A greater understanding of how learning changes with age, and particularly in older groups who show signs of motor decline (e.g. reduced speed and accuracy), is informative when it comes to considering how movement can be improved in a rehabilitation setting. Often when movement function is lost, such as post-stroke, individuals must re-learn how to use their affected limb and/or adopt new ways of compensating with their healthy limb. The present section will review literature that has examined age differences in motor learning in healthy participant groups, and **Section 1.2.3** will then consider rehabilitative approaches to movement loss after stroke. These sections therefore provide an informative introduction to the experimental work of **Chapters 6** and **7**, which detail the development of a novel sequence learning paradigm that was used to examine the effects of ageing on motor learning, and test whether learning can be improved with the use of Transcranial Direct Current Stimulation (tDCS).

Earlier in **Chapter 1**, motor learning was defined as the process of acquiring a new capability for producing movement through experience or practice (Schmidt and Vrisberg, 2008). Learning is thus an internal state that can only be inferred as having taken place by observing changes in motor performance. In other words, if learning is occurring, the learner should become closer to obtaining the desired goal of the movement (e.g. a ballet dancer can spend many hours practicing half and quarter turns before achieving the perfect pirouette). In a laboratory environment learning can be inferred, for example, when there is a reduction in the time it takes to complete a movement, or a reduction in spatial error. The improvement of motor performance over time can usual be seen in ‘learning curves’ within a single testing session (i.e. online improvements possibly reflecting short term adaptation), as well as over longer time periods usually with a break from the task and ideally after sleep (i.e. offline effects, or ‘consolidation’). Either way, motor learning is a process that demands more than simply efficient motor output – it also relies on a combination of higher-order cognitive processes, such as reasoning and memory, which allow new movements to be retained and retrieved (e.g. Rhodes, Bullock & Verwey et al., 2004; Voelcker-Rehage, Godde & Staudinger, 2010). Neuroimaging research also shows that the eventual automaticity of a new movement, which can be achieved with extended practice, yields neuroplastic changes in the brain (Ungerleider, Doyon & Karni, 2002). Given that cognitive abilities also diminish with age (e.g. Verhaeghen & Salthouse, 1997) it is reasonable, then, to predict that motor learning might be particularly challenging for older people.

A recent systematic review of fine motor learning studies by Voelcker-Rehage (2008) provides a helpful summary of research in this area – older adults tend to learn at a slower rate and with poorer final outcomes on aiming, sequence learning, grip force and augmented feedback tasks (e.g. Swanson & Lee, 1992; Harrington & Haaland, 1992; Pratt et al., 1994; Liao Jagacinski, Greenberg 1997; Swinnen, Verschueren, & Bogaerts et al., 1998; Ketcham, Seidler, Van Gemmert & Stelmach, 2002; Wishart, Lee, Cunningham & Murdoch, 2002; Voelcker-Rehage & Alberts, 2005; Shea, Park & Braden, 2006; Boyd, Vidoni & Siengsukon, 2008). There are however instances where age differences in learning have not been found, for example on some versions of sequence learning and augmented feedback paradigms (Howard & Howard, 1989; Howard & Howard, 1992; Carnahan, Vandervoort, & Swanson, 1996; van Dijk, Mulder & Hermens, 2007). This suggests that the effects of ageing on motor learning may be task-specific rather than generalised (e.g. Seidler, 2006). Voelcker-Rehage's (2008) review also implies that complex tasks have a greater likelihood of revealing age differences in learning. A relationship between age differences in motor performance and task complexity has been demonstrated in the past, whereby the effects of age on outcome variables such as RT, increase as a task becomes more cognitively demanding (e.g. Jordan & Rabbitt, 1977; Light & Spirduso, 1990). Given the decline in cognitive function that is also associated with old age (e.g. cognitive slowing, poorer working memory and reduced attention; Light & Anderson, 1985; Verhaeghen & Salthouse, 1997), an age-related deficit on more cognitively demanding motor learning tasks certainly makes sense. For example, McNay & Willingham (1998) suggested that learning in older adults is more likely to be impaired when 'strategies' can be consciously applied in explicit learning tasks (i.e. in tasks where the learner is aware that learning is taking place). In other words, an older adult is said to learn less when his/her (already limited) cognitive resources are split between the processes necessary for learning itself and the conscious formulation of an appropriate strategy. Accordingly, in McNay & Willingham's (1998) study, older adults showed impaired learning on a visuomotor transformation task that allowed the use of strategies (i.e. tracing lines with a 90° rotation where strategies such as mental rotation could improve performance), but not on a version of the task where strategies were inappropriate (i.e. when participants were told that there was no visuomotor transformation taking place).

The idea that cognitive demand might predict whether there will be age differences established on a motor learning task would certainly explain why older adults have particular difficulties with the acquisition of novel complex movement patterns (e.g. Harrington & Haaland, 1992; Boyd, Vidoni & Siengsukon, 2008). When learning a new series of movements, the sequence may require storage and/or attentional control resources based within working memory during the formation of a new long-term representation (Baddeley, 2012; Grafton, Hazeltine, & Ivry, 1995; Sakai, Hikosaka, & Miyauchi et al., 1998; Unsworth & Engle, 2005). What's more, there are age-related differences in *how* older people encode sequence information. Young people store parts of a motor sequence in 'chunks', which are internal representations of groups of elements that constitute a given sequence. Encoding sequences in this manner saves information processing resources so that instead of having to recall every move of a sequence individually, integrated sections of the array (typically three to five elements; Verwey, 1996) can be combined and recalled together (Bo, Borza & Seidler, 2009; Sakai, Kitaguchi, & Hikosaka, 2003; Verwey, 1996; Verwey, 1999; Verwey, & Eikelboom, 2003; Verwey, Abrahamse & Jiménez, 2009; Verwey, 2010). Older adults, however, do not always benefit from this encoding strategy – they instead show minimal chunking compared to the young, and even when chunking is used, the chunks have fewer elements (Shea et al., 2006; Verwey, 2010). This is supported by research on both immediate serial recall (Naveh-Benjamin, Cowan, Kilb, & Chen, 2007) and particularly in long-term association formation (e.g. Howard, Fry, & Brune, 1991; Chalfonte & Johnson, 1996; Naveh-Benjamin, 2000; Castel & Craik,

2003) indicating that older adults have generalised difficulties in forming chunks or associations in memory.

The fact that visuospatial working memory capacity predicts both movement chunk length and sequence learning in younger people (Bo & Seidler, 2009) suggests that age-related cognitive decline in working memory processes (Salthouse, 1992; Reuter-Lorenz, Jonides, & Smith et al., 2000; Bo et al., 2009; Brown & Brockmole, 2010; Schneider-Garces, Gordon & Brumback-Peltz et al., 2010) might underlie the poorer learning rates found in older adults (e.g. Humes & Floyd, 2005). Indeed, Bo et al. (2009) found that older adults had both reduced visual working memory capacity, and they produced shorter chunk lengths in a movement sequence-learning task. Positive correlations between working memory and chunk length and between chunk length and sequence learning[1] were also observed.

The presence of cognitive decline in older adults provides an explanation of why difficulty in learning new movement skills may be experienced by this group. On the other hand, this does not rule out the possibility of other factors that might also contribute to a reduction in learning ability. For example; age differences in motor performance are well-documented, but little is known about how this decline can affect an older person's capacity to learn new movements. Motor learning certainly requires higher-order cognitive processes such as reasoning and memory, but it also places demands on the motor processes that allow an action to be physically carried out. How the motor and cognitive systems interact in order to acquire a novel motor skill is an interesting topic, and the relationship between motor performance and motor learning in older adults certainly requires further empirical investigation. Accordingly, the experimental work of **Chapter 6** examines age differences in motor sequence learning, and tests the hypothesis that reduced motor sequence learning in older groups might be

[1] Though, in this case, no direct relationship between working memory and learning rate in older adults was found.

linked to an age-related decline in baseline motor performance level. Further to the benefits of gaining more insight into this particular research question, the experimental work of **Chapter 6** also involved the development of a motor learning task that was suitable for use with older and younger adults alike. This task could then be used to examine whether tDCS is able to enhance motor learning in older adults. The following **Section 1.3** explores these issues in more detail.

1.3 Rehabilitation of Movement after Stroke

Stroke, described by O'Dell (2009, p.56) as a '*sudden, focal neurological deficit due to a cerebrovascular abnormality*', is now the third leading cause of death in the USA (American Heart Association, 2008), with older adults being particularly at risk (Furberg, 1999). While stroke can lead to a number of different cognitive, behavioural, physiological and psychological disabilities, one of the most common outcomes is motor paresis. Occurring in up to 60% of stroke survivors, motor paresis (i.e. loss or impaired motor function) results when the motor pathways responsible for the planning and initiation of controlled action become disrupted or damaged (Mumford & Wilson, 2009; American Heart Association, 2008). Motor paresis is hence a strong predictor of functional disability and can often determine the extent to which a patient is able to resume ADLs (Legg, Drummond & Langhorne, 2009). Even at 6 months post-Stroke, complete recovery of function is only demonstrated in 11.6% of cases (Kwakkel, Kollen & Lindeman, 2004). The prognosis for those who fail to regain function is not good, and a particular focus in recent years has been identifying methods of improving motor recovery within this population.

How well a person recovers from stroke varies greatly. The severity of the initial trauma, the extent to which the body is capable of healing naturally, and the type of rehabilitation provided, are just a few of the factors that can influence recovery. Figure 1.2 (reproduced from Timmermans, Seelen, Willmann & Kingma, 2009), demonstrates three (overlapping) stages of the restorative processes that take place throughout stroke recovery. Firstly in the ‘acute’ phase, the body is said to recover to a limited extent passively and spontaneously. Spontaneous recovery happens mainly within the first month, when the area of inactive but living cells surrounding the lesion (termed the ‘ischemic penumbra’) is restored, and neural activity in the areas connected to the lesion is resumed (Cramer, 2008). These spontaneous changes are neuroplastic in nature; the brain reorganises itself in order to preserve function after a trauma. Examples of neuroplastic changes include the regeneration of new synapses through axonal and dendritic sprouting, and the reorganisation of neural function when representations in damaged areas are remapped onto the undamaged hemisphere or perilesional cortex (e.g. Duffau, 2006; Winship & Murphy, 2009). The remapping of functions in the undamaged motor cortex is vital for true recovery, where the same muscles used prior to the injury can be reengaged via their new cortical representations (mainly within the acute and subacute phases). In the late subacute and chronic phases, compensatory processes play a more dominant role. At this stage, the body begins to recruit alternative muscle groups, limbs and joints in order to complete functional tasks. Rehabilitation can help accelerate the acquisition of compensatory strategies in these latter stages; with particularly successful outcomes evident when provided within the first 6 months post-Stroke (Kwakkel et al., 2004).

Approaches to rehabilitation continue to advance rapidly, and the literature suggests that various interventions have the potential to accelerate functional recovery beyond levels that can be achieved spontaneously (e.g. physiotherapy, robot-assisted therapy, virtual reality motor training, pharmacological interventions, NIBS; Cramer, 2008; O’Dell et al., 2009). Nevertheless, the resources available within the National Health Service (NHS) are limited, and patients are not always happy with the services offered after discharge from hospital (Hoenig, Sanford & Butterfield et al., 2006). For example, one patient satisfaction survey involving 28 GP practices suggested a poor level of service – opportunities for follow-up appointments were limited and little information was provided about the services available to support recovery after discharge (Tyson & Turner, 2000).

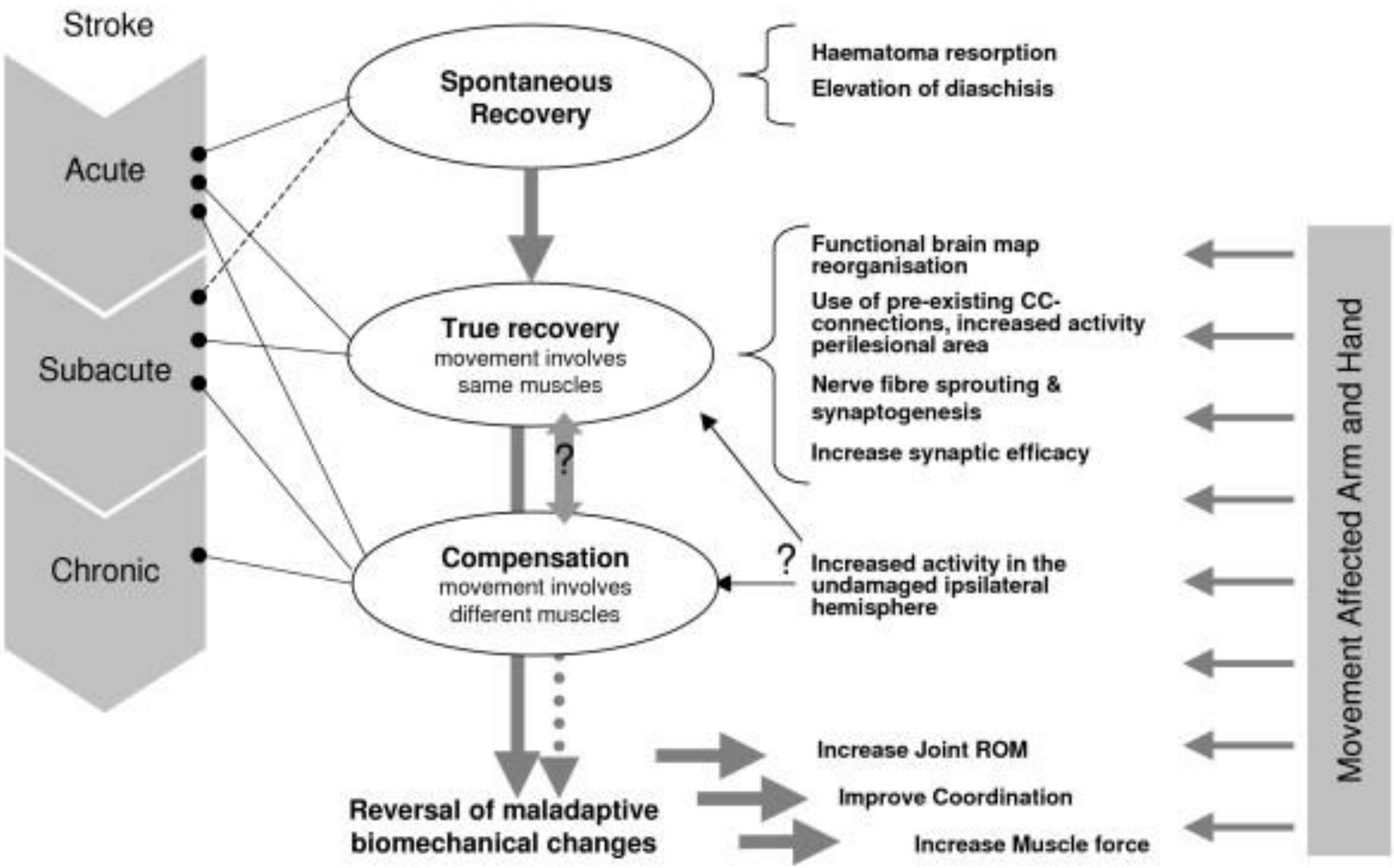

Figure 1.2 *Restorative processes that occur within three stages of stroke recovery. Reproduced from Timmermans et al. (2009).*

Clearly there is a need for rehabilitative interventions that will not only yield the greatest improvements for patients, but will do so at minimal cost to the NHS. This work in this thesis focuses specifically on Transcranial Direct Current Stimulation (tDCS), a method of NIBS. Before considering studies that have applied this technique, the following section (**1.3.1**) will describe physical therapeutic approaches to the rehabilitation of upper-limb paresis, with an emphasis on the evidence-based practice of Constraint-Induced Movement Therapy (CIMT). This provides a useful context when considering how tDCS could be used to enhance the effects of a motor training intervention in **Section 1.3.2**.

1.3.1 Physical Approaches to Rehabilitation

Approaches to physical rehabilitation differ depending on the therapist's preferred technique and a patient's physical and emotional state (Woldag & Hummelsheim, 2002). Though no 'best approach' has been identified, studies imply that some degree of physical training will help to improve motor recovery from stroke, and could, in some cases, '*mean the difference between living at home or in an institution'* (Ernst, 1990, p. 1081). What is lacking, however, is a standardised conduct of practice. For example, a recent Cochrane review argues that Occupational Therapy (OT), which aims to improve a patient's ability to resume ADLs, has promising outcomes, but at the same time requires further investigation to establish the optimal method of delivery (e.g. frequency and duration of sessions and whether OT should be combined with additional interventions; Legg et al., 2009). Furthermore, Ernst's (1990) review of physical approaches argues that many of the theories underlying the methods used by physiotherapists lack empirical support.

One of the few effective treatments that has gained support from randomised controlled trials (RCTs) is Constraint Induced Movement Therapy (CIMT). For many years, physical interventions have focused on compensation through training of the unaffected limb, whereas CIMT aims to restore function on the affected side (Taub, Uswatte &n Pidikiti, 1999;

Dromerick, Edwards & Hahn, 2000; Lum, Burgar & Shor et al., 2002; Wolf, Winstein & Millet et al., 2006; Wolf, 2007; Page & Levine, 2007; Wolf, Winstein & Millet et al., 2008; Massie, Malcolm, Greene & Thaut, 2009). The concept behind CIMT is that of ‘learned non-use’, whereby patients are found to become over-dependent on the healthy limb. This could be due to diminished cortical representation caused by the stroke itself, or a natural inclination that a patient builds towards avoiding use of the weaker limb (e.g. getting frustrated when unable to complete a particular task and so stopping attempting to perform the task in that way).

Constraint-induced approaches therefore attempt to break the cycle of non-use, and promote activation of the damaged cortex, by encouraging a patient to use his/her weaker limb in everyday activities. Typically, patients will repetitively practice activities with the damaged arm daily for two weeks, whilst the healthy limb remains restrained in a sling or mitt for up to 90% of waking hours (Taub et al., 1999). Studies that have examined the success rate of the method suggest it can improve motor function in patients with upper limb paresis (Taub et al., 1999; Dromerick et al., 2000; Wolf et al., 2006; Wolf et al., 2008; Massie et al., 2009), and also has the potential for use as a home-based therapy (Page et al., 2007). As an example, the large-scale Extremity Constraint Induced Therapy (EXCITE) trial, found greater improvements in those that underwent CIMT (e.g. indicated by arm strength, quality of movement and ADLs) than in a group who received treatment as usual (i.e. no treatment, physiotherapy or drugs). These effects were also maintained at one and two-year follow-ups (Wolf et al., 2006; Wolf et al., 2008).

Although clinical trials imply promising outcomes of CIMT, the success of this approach is still greatly limited by the restricted availability of therapists qualified to deliver the intervention, and the degree of patient co-operation required for successful outcome (Wolf, 2007). The signature treatment entails ten six-hour-long sessions with a trained OT, so provision of such an intensive service is costly. Modified versions that can be undertaken at home (e.g. Page et al., 2007) have the potential to provide a less expensive alternative, but the downside is that patients receive significantly fewer sessions with a health professional and compliance under these circumstances is not always guaranteed (i.e. because of reduced motivation by the patient). One possible solution would be to accelerate the outcomes of a physical intervention like CIMT, by pairing it with another treatment. One technique that has been used to enhance the effects of physical motor training is tDCS, a painless treatment that requires little effort from the patient and can be applied by a lone health professional (Gandiga, Hummel & Cohen, 2006). The next section will describe tDCS and provide an introduction to the evidence base that underpinned the experimental work of **Chapter 7** of this thesis.

1.3.2 Transcranial Direct Current Stimulation (tDCS)

The experimental work of **Chapter 7** combined tDCS with motor training in order to examine its effects on learning in healthy younger and older adults. Though a detailed review of the tDCS literature is provided at the start of **Chapter 7** (see **Section 7.1**), the present section will explain the tDCS method and will briefly summarise findings of studies that have applied it within healthy and stroke populations.

The concept of applying direct electrical currents (DCs) to the CNS dates back to animal research conducted in the1960s and 70s, which found that DCs could alter the electrical response of neurons (e.g. Fuortes, 1954; Hern, Landgren, Phillips & Porter, 1962; Bindman, 1962; Bindman, Lippold & Redfeard, 1964). Nowadays in human research, low amplitude DCs are delivered through saline-soaked electrodes on the scalp, in order to modify brain activity. The DCs pass through the skull to stimulate the brain and yield polarity-specific cortical effects – positive currents (Anodal tDCS; AS) enhance cortical excitability, whereas negative currents (Cathodal tDCS; CS) decrease activity in the target region (e.g. Nitsche & Paulus, 2000; Nitsche & Paulus, 2001; Nitsche, Nitsche & Klein et al., 2003a; Nitsche & Paulus, 2011; Jacobson, Koslowsky & Lavidor, 2012). The mechanism of action for these effects is found in the impact that tDCS has on neuron membrane potentials. Acting as a ‘neuro-modulator’, tDCS changes the resting membrane potential of neurons by altering the balance of ions inside versus outside of the cell; AS increases the resting membrane potential and ‘depolarises’ neurons, whereas CS decreases potentials leading to ‘hyperpolarisation’ (Nitsche, Fricke, & Henschke, 2003).

At a behavioural level, tDCS improves motor performance in healthy groups when AS is applied to the primary motor cortex (M1) to increase cortical activation and performance on the contralateral side (i.e. left hemisphere AS improves right hand performance). Cathodal tDCS can also reduce activation and enhance performance on the ipsilateral side (i.e. right hemisphere AS improves right hand performance), due to its effect on intracortical inhibition (i.e. reducing activity in one hemisphere decreases inhibition over the other hemisphere; Bolognini, Pascual-Leone & Fregni, 2009). This pattern of results seems consistent in studies with younger adults (e.g. indicated by grip force, JTT, finger sequencing and drawing performance; Boggio, Castro & Savagim et al., 2006; Vines, Nair & Schlaug, 2006; Cogiamanian, Marceglia & Ardolino et al., 2007; Vines, Nair & Schalug, 2008; Matsuo, Maeoka, & Hiyamizu et al., 2011), but lacks replication in older groups. One rare study by Hummel, Heise & Celnik et al., (2010), found that tDCS improved the speed at which older participants could complete The Jebsen Taylor Hand Function Test battery (JTT, a measure of everyday hand functions including writing and simulation feeding; Jebsen, Taylor & Trieschmann et al., 1969), but further investigation is required in order to determine which aspects of motor performance were being affected and establish whether tDCS can be used to enhance performance in a group that typically experience motor decline.

Studies that have examined the effects of tDCS on motor learning are also sparse. There is some evidence to suggest that tDCS can improve learning in younger groups, mostly on sequence learning tasks (e.g. Nitsche, Schauenburg and Lang et al., 2003; Reis, Schambra & Cohen et al., 2009; Kang & Paik, 2011; Stag, Jayaram & Pastor et al., 2011; Tecchio, Zappasodi

& Assenza et al., 2010; Tanaka, Sandrini & Cohen, 2011). However, future research must clarify the impact of factors such as electrode polarity (i.e. AS, CS or dual-hemispheric), timing of delivery (e.g. pre, during or post-training) and the intensity/frequency of sessions (e.g. current intensity and multiple vs. single sessions) on outcome. For example, some studies suggest that dual-hemisphere set-ups that involve simultaneous AS and CS may yield even greater improvements in learning than either intervention alone (i.e. uni-hemispheric AS or CS; Vine, Cerruti & Schlaug, 2008). Whereas other experiments have found the outcomes of dual tDCS to be no greater than those achieved with uni-hemispheric AS (e.g. Kang & Paik, 2011). Stagg et al., (2011) also found that tDCS led to poorer learning when applied before rather than during a sequence learning task, suggesting that the timing of delivery may be vital to outcome. Most importantly, these findings need to be replicated in the older population. To the author's knowledge, no study has yet assessed whether tDCS can improve motor learning in healthy older adults. The main body of evidence to suggest tDCS might be of benefit within this population is found in studies with clinical groups, such as patients presenting with motor problems following stroke.

The capacity for tDCS to modulate cortical activity could indeed make it a useful tool for changing a dysfunctional network, or suppressing maladaptive processes that can occur in the brain following damage (Zimmerman & Hummel, 2010). The plasticity of the human brain means that some degree of functional recovery can be achieved after stroke via cortical reorganisation (Byrnes, Thickbroom, Phillips & Mastaglia, 2001), which tDCS could enhance as a neuro-modulator (Bolognini et al., 2009; Bastini & Jaberzadeh, 2012; Schabrun & Chipchase, 2011). Applying tDCS over the M1 in the damaged hemisphere (i.e. to increase activity), and/or CS to the undamaged hemisphere (i.e. to reduce inhibition) would be the theoretical basis of this approach.

Accordingly, AS and CS have been found to improve motor performance in studies conducted with patients in the chronic phase of stroke with mild-to-moderate motor impairment (Boggio, Nunes & Rigonatti et al., 2007; Celnik, Paik & Vandermeeren et al., 2009; Fregni, Boggio & Mansur et al., 2005; Hummel & Cohen, 2005; Hummel, Celnik & Giraux et al., 2005; Hummel, Voller & Celnik et al., 2006; Kim, Ohn & Yang et al., 2009), with effects lasting for 60min after a single tDCS session (Kim et al., 2009), or for up to two weeks when tDCS was applied on five consecutive days (Boggio et al., 2007). No benefit of tDCS has been observed, however, when used with patients in the acute phase of stroke (e.g. Rossi, Sallustio & Legge et al., 2012).

The former findings are promising, but a limitation common to all of these studies is that they lacked sensitive outcome measures. One example is that most of the tDCS research with stroke patients has relied on combined measures of speed and accuracy (the limitations of which were discussed in **Sections 1.2.1.1** and **1.2.1.2** of this chapter). The problem with using a single or a combined speed-accuracy measure when working with clinical groups (e.g. the JTT, where scores are based on how quickly a participant can complete a subset of hand movement tasks), is that participants might trade-off speed and accuracy in a strategic compensation for motor decline, (this argument is explored further in **Chapters 2** and **3** of the thesis) and effects could be missed that are present in other aspects of performance.

It was also mentioned earlier in this section that tDCS might be a useful adjunct to another form of physical intervention. A proof-of-concept study with healthy young adults found that combined CIMT and tDCS improved JTT performance relative to a sham intervention (Williams, Pascual-Leone & Fregni, 2010). However, to the authors knowledge, similar outcomes in trials with stroke patients have only been established in two other studies (Lindenberg, Renga & Zhu et al., 2010; Bolognini, Vallar & Casati et al., 2010) – in both cases dual-hemispheric tDCS and physical therapy improved motor outcomes relative to sham. Conversely, another trial that combined robot-assisted therapy with tDCS, established no improvements in motor function beyond what could be achieved with a sham intervention (see abstract – Werner, Hesse, Kroczek & Waldner, 2008).

Future research should therefore aim to elucidate the outcomes of tDCS in older populations as well as in clinical groups, and most importantly, seek to develop more sensitive methods for assessing motor outcome. Alberts and Wolf (2009) specifically singled out the value of kinematic analysis for the objective examination of hand function in cases of stroke. In their work, kinematic measures were used to assess forces produced in a bimanual dexterity paradigm (i.e. pulling two objects apart). Furthermore, Kwakkel, Boudweijn & Krebs' (2008) review of robot-assisted interventions for upper-limb paresis argues that kinematic methods (more so than functional scales such as ADLs) are more likely to distinguish between signs of genuine recovery and changes that occur as a means of compensating for motor decline. The following section accordingly describes the kinematic assessment tool used to develop tasks and measure movement in the experimental work of this doctoral thesis. While stroke patients were not recruited for the studies in this thesis, kinematic motor tasks were designed with a view to future use within clinical populations.

1.4 Task Design and Kinematic Analysis

Kinematic analysis allows many of the individual characteristics that govern a particular movement to be independently and objectively assessed. In the experimental work of **Chapter 2** and **4-7**, a sophisticated digitised kinematic assessment tool that captures the horizontal and vertical movements of the hand (X and Y coordinates) was used to develop a series of motor tasks ('KineLab'; Culmer at al., 2009). The advantage of KineLab over the kinematic techniques used to measure hand coordination in the past is that it allows researchers to design visual-spatial tasks *and* independently record a number of kinematic outcomes (e.g. RT, MT, accuracy, jerk, pressure etc), through its integration with any commercially available tablet PC (see Figure 1.3). When KineLab is installed on a tablet laptop, the adjustable screen can be rotated and folded backwards to provide '*a digital equivalent of a pen and paper*' (Culmer et al, 2009, p. 186.). This is both practical and reliable. For example, in Morgan et al's (1994) kinematic study, task targets had to be displayed on plastic sheets attached to the graphics tablet in order to minimize friction, which is more cumbersome and less precise than an integrated system like KineLab.

Figure 1.3 *KineLab tracing task on standard tablet PC, with digitised stylus.*

The portability of KineLab also makes it particularly useful when working with older adults (and potentially clinical groups). Many older people lack transport to the lab and therefore prefer to be tested at home. Likewise, clinical populations will often need to be assessed at the hospital or in outpatient clinics. KineLab has also been programmed to plug-in to a range of different input devices – a digitised stylus, standard PC mouse, joystick etc. This means that the equipment can be personally tailored to suit the characteristics of any participant group (e.g. if the precision grip necessary for controlling the stylus is problematic for stroke patients, a joystick can be used as an alternative). Most importantly, KineLab has been found to distinguish reliably between poor and proficient motor performance in healthy younger and older adults alike (see Raw, Kountouriotis, Mon-Williams & Wilkie, 2012; Raw, Wilkie, Culmer & Mon-Williams, 2012. Data from these published articles can be found in **Chapters 2-4**).

Each of the following experimental chapters provides detailed descriptions of how motor tasks were designed and implemented within KineLab. **Figures 1.4** and **1.5** display screen shots of two of the interfaces used by the researcher when manipulating visual stimuli (**1.4**) and selecting outcome measures (**1.5**) in the task designer. For a comprehensive account of how the KineLab system itself was developed, see Culmer et al., (2009).

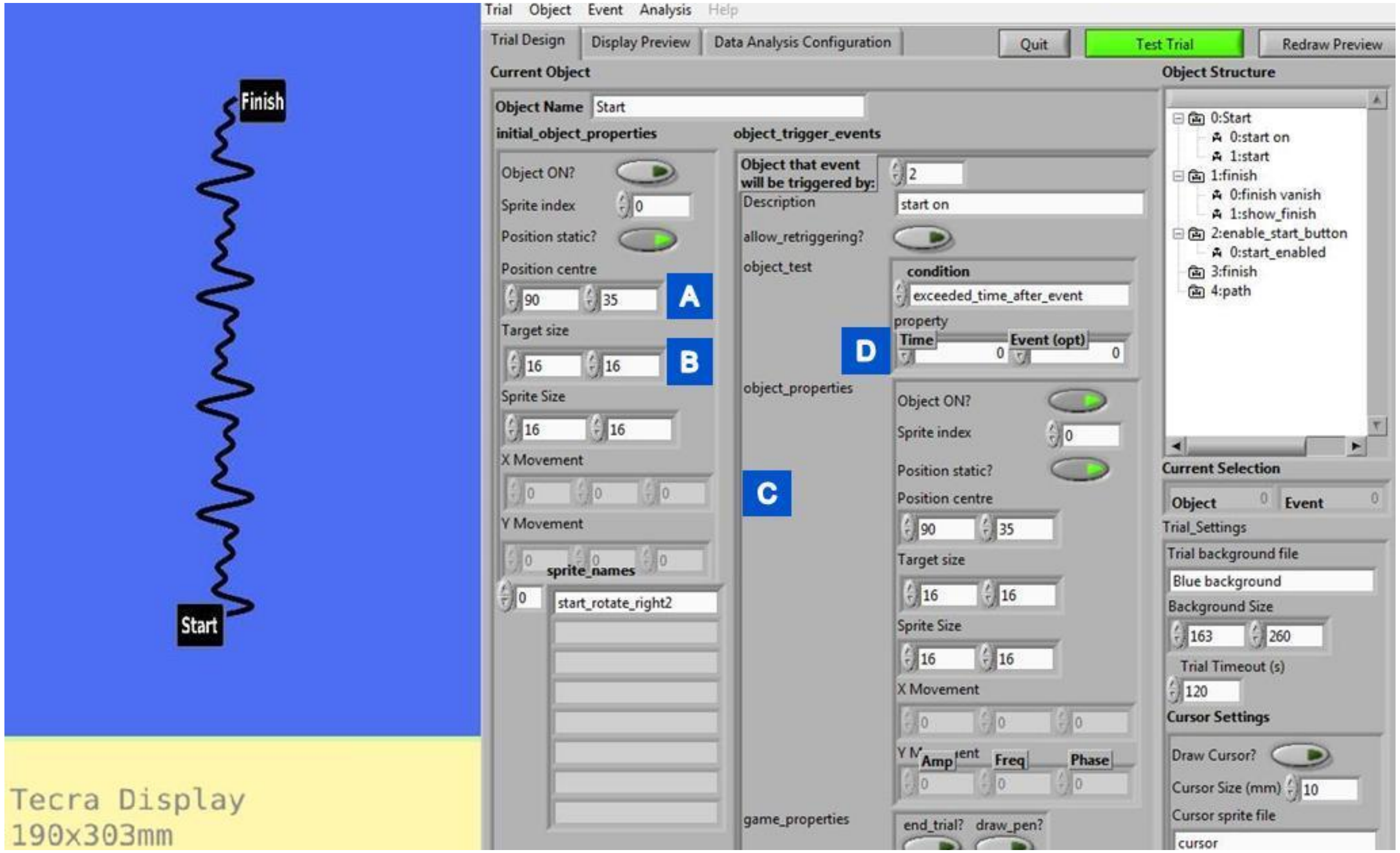

Figure 1.4 *Screen shot of the Trial Design feature of the KineLab Trial Designer, which allows researchers to upload visual stimuli (e.g. a sinusoidal-shaped path in the featured example) and manipulate characteristics such as positioning **(A),** size **(B)** and movement **(C).** Trials are created by adding and/or removing 'objects' (i.e. stimuli) and 'events' (i.e. commands that control the stimuli) to the 'object structure' on the right side of the user interface **(D)**.*

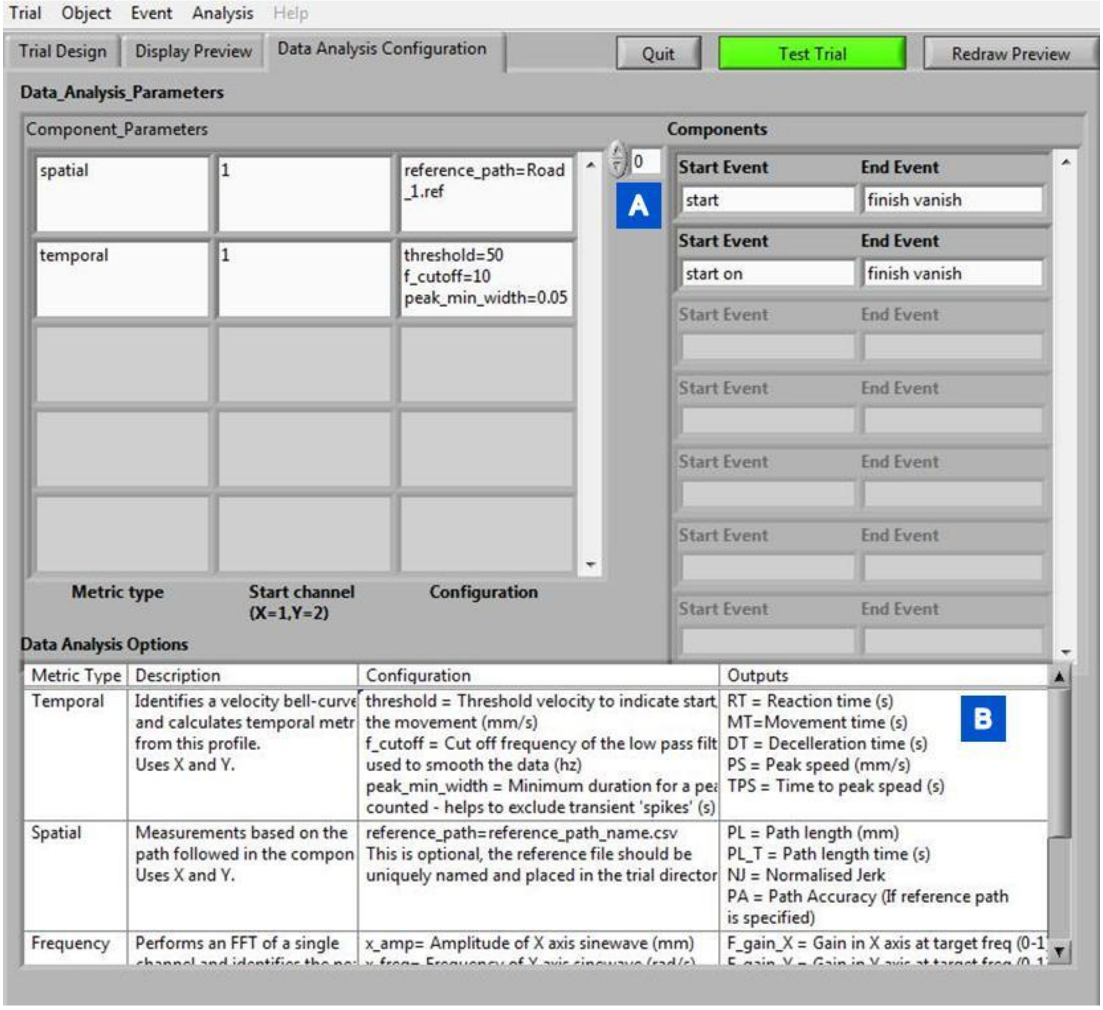

Figure 1.5 *Screen shot of the Data Analysis Configuration feature of the KineLab Trial Designer. The researcher can* ***(A)*** *specify when to record movement (i.e. a beginning and endpoint for measurement); and* ***(B)*** *select from a number of different kinematic outcome measures.*

1.5 Research Aims and Thesis Structure

Age-related changes in the motor system can make it increasingly difficult for older adults to execute movements with the same level of speed and accuracy as their younger counterparts. This thesis aims to examine the precise nature of this motor decline, and whether there are methods that can be reduce the impairment. As outlined in **Section 1.2**, older adults show decrements in performance across a range of motor tasks, but more sensitive methods of assessment are required. A comprehensive approach to measurement is particularly important when examining movement in a group that is likely to adopt strategies to compensate for motor decline (**Section 1.2.1.1**), and when trying to detect subtle differences between the two hands (**Section 1.2.1.2**). Further investigation into the effects of ageing on motor learning is also necessary. Past studies suggest that age-related changes in learning are task-specific (**Section 1.2.2**) though what mediates this relationship is unclear (e.g. does poor motor performance predict poor learning?). In the rehabilitation literature for post-stroke paresis (**Section 1.3**), a need has been highlighted for the improvement of current methods to accelerate motor recovery while keeping costs low (**Section 1.3.1)**. This could potentially be achieved with the use of tDCS, which has been found to improve motor performance and learning in healthy young adults (**Section 1.3.2**). Such findings, however, lack replication in older populations, and studies with stroke patients have tended to rely on suboptimal outcome measures (e.g. combined measures of speed and accuracy or a single outcome metric).

Accordingly, this doctoral research relied upon sophisticated kinematic technology to objectively assess age differences across a series of different motor tasks. In response to calls for further research within this topic area, the following **primary aims** were set (i) to create kinematic tasks to examine specific questions regarding age differences in motor performance; (ii) to create a task to measure and infer potential causes of age-related differences in motor learning; and (iii) to use the motor learning task to assess the outcomes of tDCS in healthy younger and older adults. All experimental tasks were also designed with a **secondary aim** in mind**;** to produce sensitive tests for assessing movement that have the potential for use within a rehabilitative setting. Kinematic methods of assessment will be of particular value in a clinical context as they go beyond indicating whether or not a movement has improved (e.g. if a patient can button his or her shirt), but instead can also inform the researcher and/or clinician regarding which aspects of movement may or may not be responding to a given intervention (e.g. precision, speed, grip force).

To summarise the thesis structure – the first of the primary aims is met in the experimental work of **Chapters 2-5**, which examines age differences in motor performance. **Chapters 6** and **7** focus on motor learning and tDCS and therefore address the second and third aims. **Chapter 8** closes the thesis by summarising the research findings of **Chapters 2-7** and identifying any limitations of that work. The final chapter also describes future objectives and how the secondary aim was fulfilled in securing post-doctoral funds for further research with stroke patients.

Chapter 2
Age Differences in Motor Performance: Path Tracing

2.1 Introduction

As outlined in the introductory **Chapter 1**, ageing is associated with a decline in motor performance, whereby movements become slower, less accurate and more variable with increasing age (e.g. Schmidt & Lee, 1999). This decline can be explained by changes in physiology including a reduction in sensory sensitivity, deterioration in strength and flexibility of the limbs (Barnett & Cobbold, 1968; Delbono, 2003), and an increased susceptibility to diseases that affect movement (e.g. stroke, arthritis etc). The impact of these changes is inevitably profound and can greatly limit the extent to which older people are capable of undertaking everyday tasks of daily living (Giampaoli, et al., 1999; Rantenen et al., 1999).

It is not surprising then that older adults also show decrements in performance when faced with behavioural tasks that examine movement speed and accuracy in a laboratory environment. For example, in simple motor coordination tasks (which require the two or more joints interacting to execute fast and repetitive movements within a set time frame), older adults take a longer period of time to achieve the same movement goals as their younger counterparts (e.g. Desrosiers et al., 1995; Verkerk, Schouten & Oosterhuis, 1990). While aging causes a direct reduction in the speed at which movements can be carried out, it is possible that this age-related slowing is also driven by compensatory processes. Evidence suggests that humans are able to rapidly assess their intrinsic motor variability and optimize their motor strategies (Trommershäuser et al., 2005). One strategy is generating slower actions to make it easier to use on-line feedback to make corrective adjustments. An increase in movement duration can, therefore, allow older adults to perform at an equivalent level of spatial accuracy to a younger population, with decrements only becoming apparent when there is an external timing constraint imposed upon the task (Morgan et al., 1994; Welsh et al., 2007).

It can be seen that there are two possible interpretations of an increase in movement duration as a function of age – it could be (i) a direct consequence of age-related physiological changes, or (ii) a strategic response to these changes. Strategic compensation does not necessarily mean that behaviour is adjusted through conscious control. Older adults may consciously attempt to compensate for their difficulties and/or adapt to increased signal variability in a cognitively impenetrable manner (Desrosiers et al., 1995; Krampe, 2002; Smith, Umberger & Manning et al., 1999; Verkerk et al., 1990).

When it comes to interpreting motor performance in a laboratory or clinical environment, practical issues arise. In a motor task it can be difficult to detect changes in movement as a function of age when spatial accuracy is used as a measure; unless task duration is carefully controlled (i.e. participants may slow down to preserve accuracy). Furthermore, in rehabilitation settings, encouraging an individual to speed up his/her movements might actually interfere with his/her own successful strategic compensation. Accordingly, it can be seen that there are good scientific and clinical reasons for understanding both the quantitative and qualitative changes that occur in movement as a function of age. The aim of the experiment in this chapter was therefore to explore whether older adults make spatial and temporal adjustments to their movements in order to meet the demands of a manual control task.

The relationship between movement speed and accuracy was first formally defined by Fitts in 1954. Fitts (1954) proposed that the time taken to complete a movement is a function of movement amplitude and target size. The relationship between duration and task parameters has been examined extensively within the movement literature (Plamondon & Alimi, 1997 provide a full review) and it has been established beyond a doubt that increasing accuracy demands (e.g. by decreasing target size) produces a lawful increase in movement duration – the so-called ‘speed-accuracy trade-off’. In order to determine whether there are general strategies used to compensate for age-related deficits, the experiments in the present chapter examined the relationship between speed and accuracy, and age differences in this relationship, in a tracing task.

Previous comparisons of hand-writing and walking movements have demonstrated that there are general patterns of behaviour that emerge during both actions (Hicheur, Vieilledent, Richardson, Flash & Berthoz, 2005). Moving the hand to trace a path has the classic characteristics required to examine speed-accuracy trade-offs as well as strategic compensation (Johnson, Culmer, Burke, Mon-Williams & Wilkie, 2010). Visual feedback about hand position relative to the path edge can allow an individual to stay within a wide path when moving slowly. If the accuracy demands are increased (i.e. the path becomes narrower) then speed should reduce, or if the speed is increased then accuracy should be impaired. If there is increased visual-motor variability with age then it could also be expected that older adults would produce slower speeds and/or the adoption of movements that trace closer to the path centre (to avoid leaving the path).

The tracing task itself was created using the kinematic assessment tool, KineLab, (Culmer et al., 2009), and required participants to trace paths of variable thickness with a digitised stylus (i.e. similar to a ballpoint pen). In two of the task conditions, speed was controlled (using a set fast or slow speed dictated by a moving ‘window’), so that spatial strategies could be examined under a temporal constraint. A condition was also included whereby participants were able to move at their own (i.e. unconstrained) pace, to allow age differences in speed-accuracy selection (and trade-off) to be analysed. The participants were instructed that their trajectory must not leave the delineated path and, when time was unrestricted, that they must complete the task as quickly as possible. One of the paths was sufficiently thin to ensure that the task had to be completed by tracing the path's shape exactly, but also included were two thicker paths where the finish point could be reached faster in the preferred speed condition by cutting-the-corners. Because this corner-cutting strategy risks error (i.e. leaving the path), it would be safer to take longer in the preferred speed condition, and stick to the middle of the path. In light of the increased motor variability associated with older age, it was therefore expected that when older participants were pacing themselves, they would stay closer to the middle of the path to reduce the risk of crossing outside of the path boundary. On the other hand, it was anticipated that the less variable younger adults would cut-the-corners in order to reach the finish-line in a shorter period of time. Finally, it was of interest to identify whether any age difference in spatial strategy would remain when movement duration was pre-set - would participants still cut-the-corners when they could not achieve shorter overall movement duration?

2.2 Method

The following sections describe the methodology used to carry out the experiment. **Section 2.2.1** provides details of the participants recruited for the study and **2.2.2** describes how the movement task was designed and implemented. The outcome measures of interest are defined in **Section 2.2.3**, along with the chosen method for data analysis.

2.2.1 Participants

Twenty seven healthy individuals with no history of ophthalmological or neurological problems were tested from an opportunistic sample (NB. individuals were recruited from the University of Leeds and a local amateur dramatics society, Teesside Musical Theatre Company). All participants were right-handed as indexed by the Edinburgh Handedness Inventory (EHI; Oldfield, 1971) with an average score of 90.26 (*SD* = 13.88) out of the maximum 100 (scores of +40 indicate right-handedness; see *Appendix A* for a copy of the test and scoring criteria). Participants were split into two age groups, though one young participant was excluded because their RMS error scores exceeded the group mean by over three standard deviations. After exclusion, the young group consisted of 13 participants (6 females, 7 males) aged between 18 and 38 years (mean age = 27.69, *SD* = 6.06). The old group comprised 13 people (11 females, 2 males) aged between 62 and 80 years (mean age = 69.62 years, *SD* = 5.39). The University of Leeds ethics and research committee approved this study and all participants gave written, informed consent in accordance with the Declaration of Helsinki.

2.2.2 Procedure and Apparatus

The tracing task was created with 'KineLab' (Culmer et al., 2009), a kinematic assessment tool used to design visual-spatial tasks and record the X and Y co-ordinates of hand movement. Participants used a handheld stylus (stylus length = 150mm; nib length =1mm) to draw along paths presented on a tablet PC, whereby the screen (width = 260mm; height = 163mm) was rotated and positioned flat to the table top (i.e. similar to a pen-and-paper style task). Each path was the same shape (measuring 184.3 mm in height from top to bottom, and 19.8 mm in width from left to right), but varied in thickness (2 mm, 4 mm, 6 mm). The speed at which participants were required to trace also varied between trials. Two of the conditions were set at a constant speed whereby the path was presented within a moving 'window' (i.e. 2 bars spaced 250mm apart) which moved along and gradually revealed the future path whilst the path behind disappeared (see Figure 2.1a). This occurred at a rate of 12.86mm/s in the slow condition and 23.64 mm/s in the fast condition. A third condition was also included in which participants were able to trace at their own preferred pace. In this condition the path was static and fully visible throughout the trial (see Figure 2.1b). Each path thickness (narrow, medium and wide) was presented five times within each of the speed conditions (slow, fast, preferred) resulting in a total of 45 paths to trace (presented in a random order). Participants completed the task using their (preferred) right hand and were provided with the following instructions; "*follow the path from start to finish as quickly as possible. You must NOT go outside of the path".*

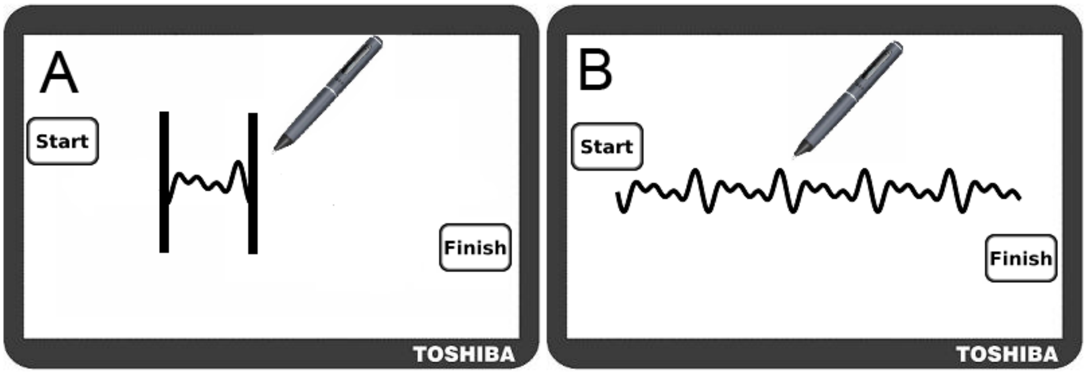

Figure 2.1 *Screen shots taken from the KineLab tracing task as the stimuli appeared to participants on the tablet PC screen (NB. not to scale).* ***(A)*** *An example of a set speed trial with the narrow path****. (B)*** *An example of a preferred speed trial with the narrow path.*

2.2.3 Analysis

The following measures of tracing performance were calculated: (i) **Movement Time (MT)**, the time taken (in seconds) from the moment the stylus exited the start icon until the point at which the stylus crossed into the finish icon, (ii) **Path Length (PL)**, which indicated the extent to which participants cut the corners by recording the length of the trace from start to finish, and (iii) **Root Mean Squared Error (RMSE)**, the average distance of the stylus from the closest reference point on the middle of the path. Each individual's mean score for the three path thickness conditions and the three speed conditions was calculated for each measure (MT, PL and RMSE). These data were then input into separate mixed ANOVAs to examine differences between the task conditions and age groups. Greenhouse-Geisser estimates of sphericity (ε) are reported where degrees of freedom have been adjusted.

2.3 Results

Figure 2.2a displays the mean Movement Time (MT) for the young and old groups on the narrow, medium and wide paths, in the controlled slow, controlled fast and preferred speed conditions. The ANOVA revealed significant main effects for path thickness (F (2, 48) = 38.82, $p < .001$, η^2_p = .62, ε = .59) and speed condition (F (2, 48) = 386.58, $p < .001$, η^2_p = .94, ε = .52), and a path thickness × speed interaction (F (4, 96) = 58.99, $p < .001$, η^2_p = .71, ε = .32). While there was no main effect of age (F (1, 24) = 2.65, $p > .05$, η^2_p = .10), nor interactions between age and path thickness (F (2, 48) = .12, $p > .05$, η^2_p = .005), and no three-way interaction (F (4, 96) = .07, $p > .05$, η^2_p = .003), there was a significant age × speed interaction (F (2, 48) = 6.41, $p < .001$, η^2_p = .21, ε = .51). Figure 2.2a shows that path thickness did not greatly alter MT when speeds were held constant, but thicker paths did result in shorter MTs during preferred speed trials. This shows that the 'set speed' trials successfully controlled speed, with the old and young participants having the same MTs in slow and fast conditions. The interaction between age and speed results from the preferred speed condition whereby there was a general increase in MT for the old group compared to the young. The lack of interaction between age and path thickness does indicate, however, that MT reduced by a similar amount as paths increased in thickness for both age groups. In terms of speed/accuracy trade-offs it therefore seems that the old adopted slower speeds overall, but did not moderate speed differently compared to the young.

Because MT decreased on wider paths when moving at the preferred speed, it can be anticipated that participants may have been 'cutting-corners' to reduce the distance the pen needed to travel from start to finish. To confirm corner-cutting behaviour, Path Length (PL) was examined. The 'ideal' PL was calculated for the centre of the reference path and data showed that the paths taken by participants were generally shorter than this value (shown by the horizontal dashed line on Figure 2.2, right-hand panels). For clarity of presentation, the mean PL on the narrow, medium and wide paths, in the set slow, set fast and preferred speed conditions are shown separately for the young group in Figure 2.2d and for the old group in Figure 2.2f. The ANOVA for PL revealed a significant main effect of path thickness (F (2, 48) = 307.16, p < .001, η^2_p = .93, ε = .58) and speed (F (2, 48) = 6.63, p < .001, η^2_p = .22, ε = .69), as well as a path thickness × speed interaction (F (4, 96) = 13.39, p < .001, η^2_p = .36, ε = .61). There was no main effect of age (F (1, 24) = .660, p > .05, η^2_p = .03), nor interactions between age and speed (F (2, 48) = .13, p > .05, η^2_p = .005), and no 3-way interaction (F (4, 96) = 2.05, p > .05, η^2_p = .08). However, there was a significant age × path thickness interaction (see Figure 2.2b and 2.2h, F (2, 48) = 9.06, p < .001, η^2_p = .27, ε = .58).

The general pattern across conditions shows that PL decreased as the path got thicker, indicating that there was a tendency for participants to cut-corners on these paths. Furthermore, PL was reduced when participants were tracing at faster speeds. The path thickness × speed interaction reflects the different gradients of the lines shown in Figures 2.2d and 2.2f, whereby different speed conditions were affected to a greater or lesser extent by the thickness of the path. These differences demonstrate two things – (i) while there was little difference in PL between the set fast and slow conditions on narrow paths, PL decreased more for wider paths at fast speeds than at slow (i.e. there was most corner-cutting on wide paths at fast speeds), and (ii) while there was little difference in PL for the fast and preferred speeds conditions on the wide paths, PL increased more on the narrow paths at preferred speeds than at fast speeds (i.e. there was less corner-cutting on narrow paths at preferred speeds). While the patterns for PL in old and young were similar, the path thickness × age group interaction indicates that older participants were less likely than the young to cut-the-corner as the path got thicker (see Figures 2.2b & 2.2h).

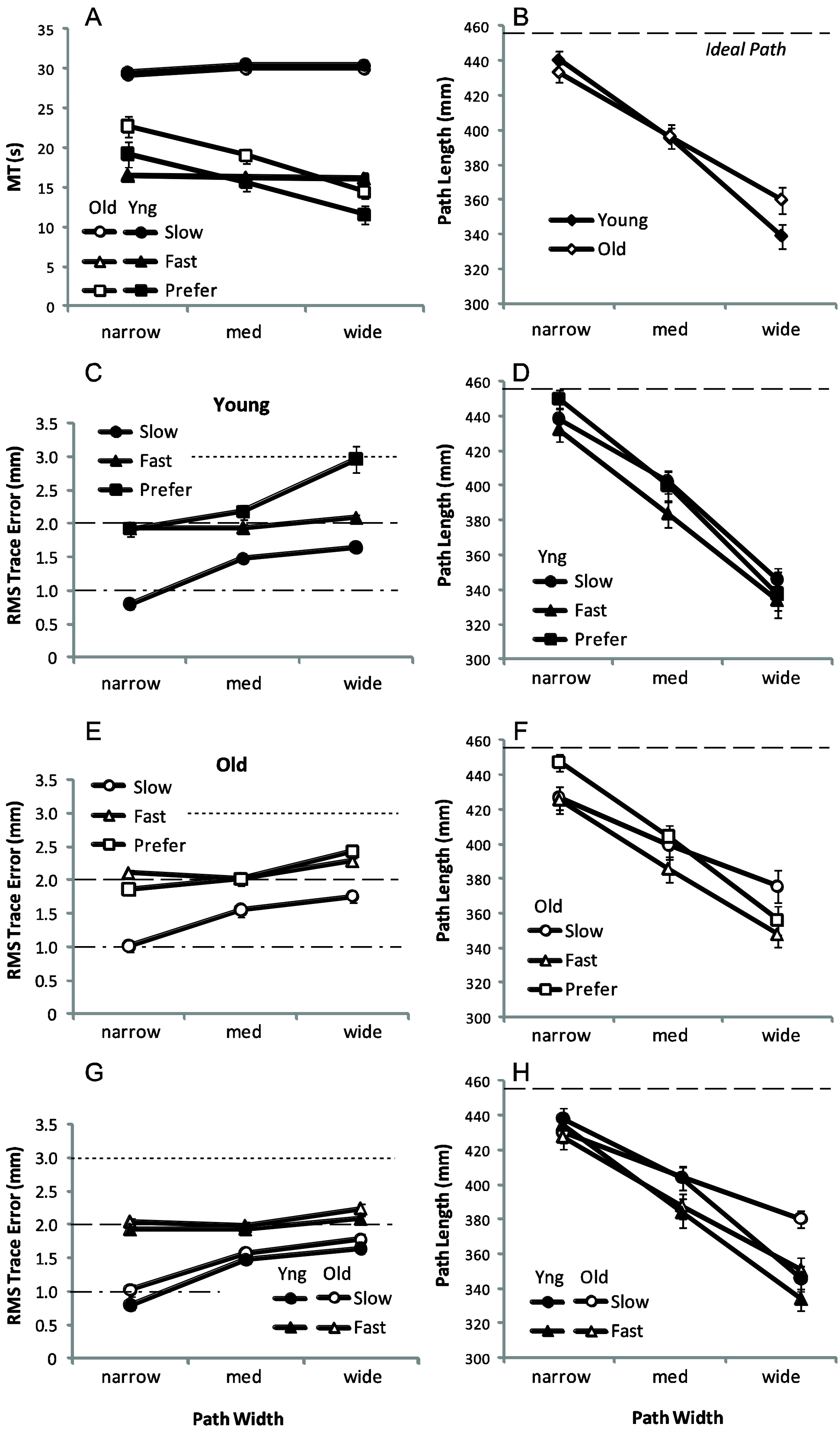

Figure 2.2 (caption overleaf)

Figure 2.2 *(p. 43) Tracing performance on the narrow (2mm), medium (4mm) and wide (6mm) paths at the slow (circles), fast (triangles) and preferred (squares) speeds for the young (filled symbols) and old (open symbols) groups:* ***(A)*** *Movement Time (MT),* ***(B)*** *Path Length for the Young and Old averaged across speed conditions,* ***(C)*** *Root Mean Square Error (RMSE) for the young,* ***(D)*** *Path Length (PL) for the young,* ***(E)*** *RMSE for the old,* ***(F)*** *PL for the old****,*** ***(G)*** *RMSE for the young and old for constrained speed conditions,* ***(H)*** *PL for the young and old for constrained speed conditions. Horizontal dashed lines indicate the 'ideal' path length tracing the path centre (panels B,D,F,H). Horizontal dotted/dashed lines indicate the maximum error (half path width) to stay within the narrow (2mm, dot/dashed line), medium (4mm, dashed line) or wide (6mm, dotted line) paths (panels C, E G). Bars = Standard Error of the Mean.*

An increase in PL could theoretically be explained by more erroneous tracing (e.g. 'wobbly' or zigzag'' trajectories)., rather than tracing the path more accurately To confirm that the longer trajectories did indeed follow the path more accurately RMSE was calculated – the distance of the pen from the middle of the reference path at each time-point. The mean RMSE for narrow, medium and wide paths, in the set slow, set fast and preferred speed conditions are shown for the young group in Figure 2.2c and for the old group in Figure 2.2e. The ANOVA for RMSE revealed a significant main effect of path thickness (F (2, 48) = 224.188, p < .001, η^2_p = .82, ε = .75) and speed (F (2, 48) = 114.4, p < .001, η^2_p = .83, ε = .64), as well as a path thickness × speed interaction (F (4, 96) = 26.11, p < .001, η^2_p = .52, ε = .69). These results confirm that an increase in PL was associated with improved tracing accuracy (and hence reduced RMSE).

The reduced corner-cutting (increased PL) observed in the old when tracing wide paths could be explained by a general preference for accuracy (and hence slower MTs when unconstrained). To determine whether the older adults were more accurate, age-related results from the ANOVA were examined. There was no main effect of age (F (1, 24) = .011, p > .05, η^2_p =

0), nor an age × path thickness interaction (F (2, 48) = 2.30, $p > .05$, η^2_p = .09). There was, however, an interaction between age and speed (F (2, 50) = 6.47, $p < .01$, η^2_p = .21), and a 3-way interaction (F (4, 96) = 2.73, $p < .05$, η^2_p = .10). The interactions occur because the older adults were more accurate in only one condition: tracing wide paths at preferred speeds (t (24) = 2.32, p = 0.03). The young sacrificed accuracy to follow faster trajectories that cut-the-corners. In all other conditions the older adults were no better than the young (Figure 2.2g). To determine whether the old had decreased motor skill, RMSE was compared on the narrow path at the slow speed across age groups (since this condition should reflect the greatest possible accuracy). As expected by the interactions, the young were better in this condition and stayed significantly closer to the path centre (Figure 2.2g; t (24) = 2.08, p = 0.04).

2.4 Discussion

This experiment provides new insight into the effects of ageing on motor performance. Previous research has identified an age-related decline in movement speed, accuracy and consistency (e.g. Desrosiers et al., 1995; Verkerk et al., 1990; Morgan et al., 1994; Welsh et al., 2007). The results support previous findings, but also indicate that older adults adopt a different movement strategy when faced with a motor task that requires them to move steadily under temporal and/or spatial task constraints. This was demonstrated by separately analysing speed and accuracy in a manual tracing task. Analyses revealed a tendency for older adults to remain closer to the middle of the path and slow their movements down when possible (relative to their younger counterparts), in order to avoid leaving the path. This suggests that older adults are sensitive to their level of motor skill and are capable of adjusting their movement strategy in order to meet task demands.

The kinematic variables measured in this experiment were movement times (MT), error (RMSE) and path length (PL), and these outcomes were assessed under conditions that required participants to trace paths of varied thickness at either their own pace, or under a temporal constraint (i.e. a controlled slow or fast pace). When speed was controlled there was little difference in MT between the path thickness conditions, but when participants traced at their preferred speed, thicker paths yielded shorter MTs. The fact that there was no interaction between age and path thickness on this measure suggests that the effect of path thickness on MT was not dependent on age. Hence the MTs of the old and young decreased by a similar amount as the path got thicker (i.e. all participants speeded up when there was more room for manoeuvre). On the other hand, the significant interaction found between age and speed condition suggests that when moving at their preferred speed, the older participants traced more slowly than the young. In other words, when placed under a temporal constraint the old and young traced at a similar speed, but when pacing themselves, the older participants preferred to reduce their speed. This is understandable since the older adults were worse at tracing the narrow path under constrained slow speeds, indicating a (somewhat predictable) deficit in visual-motor control. But was there any evidence of older adults compensating for their reduced level of skill?

Using the error and PL measures, it was possible to further explore the effects of path thickness and speed, specifically on corner-cutting behaviour. The strategy of ‘cutting-the-corners’ is especially risky when motor variability is high (e.g. in older adults), because it involves moving the stylus much closer to the outside path boundaries and so increases the risk of leaving the path. Accordingly, the PL data indicated an increase in corner-cutting (and hence a decrease in PL) as the paths got thicker, which reflects the greater margin for error either side of the pen when tracing along a thicker path. There were also age differences in corner-cutting behaviour whereby older participants were less likely to cut-the-corner as path thickness increased (Figure 2.2b). It seems then that the older participants were indeed sensitive to their limitations, and therefore preferred to slow down where possible and keep the pen closer to the middle of the path in order to compensate for motor variability.

In conclusion, the findings of the present experiment both confirm previous reports of motor slowing and variability in older adults (e.g. e.g. Desrosiers et al., 1995; Verkerk et al., 1990; Morgan et al., 1994; Welsh et al., 2007), and add to our knowledge of how older people might try to compensate for motor decline. The use of a manual tracing task to measure spatial and temporal differences between old and young participants essentially revealed a tendency for older people to slow their movements down and adjust their spatial strategy to avoid error (i.e. reduced corner-cutting on the wider paths relative to the young).

The findings of this experiment have two primary implications for future research. Firstly, the possibility that older adults are not only sensitive to their difficulties, but are also able to adjust their movement strategy accordingly, poses implications for the approach to motor rehabilitation in the future. Critically, it is important to establish how older people learn (whether consciously, or unconsciously) to adapt to their new diminished level of skill before prompting or teaching new methods in a rehabilitative setting. Secondly, in the context of this doctoral thesis, this study provides evidence that KineLab is an effective tool for distinguishing reliably between poor and proficient manual ability. The equipment was particularly well-suited to the testing of older participants as the pen-and-paper style set-up that was reminiscent of a handwriting task felt familiar and required little explanation (this was confirmed through verbal reports).

This study also raises an important question with regards to whether the patterns of motor behaviour observed in a simple tracing task can translate to real-life movement scenarios. For example, if older adults are indeed capable of adjusting their motor strategy to meet task demands, does this mean that similar or other specific strategies are used in everyday tasks? Given the tendency for older adults to apply a ‘middle-of-the-path’ strategy when tracing paths, it is important to establish whether older people use the same strategy when navigating in the real world (e.g. a middle-of-the-road strategy when driving). Accordingly the next chapter explores the generalisability of the present findings to a task that required participants to steer along roads of variable thickness in a simulated driving environment under different temporal constraints.

Chapter 3
Age Differences in Motor Performance: Simulated Driving

3.1 Introduction

The previous chapter examined age differences in performance using a tracing task with different spatial and temporal constraints. It was found that older adults slowed down their tracing movements in conditions where there was no speed restriction, suggesting a preference for spatial accuracy over speed. Older participants also kept the stylus closer to the path midline as path thickness increased. This contrasted with the behaviour of the younger group who adopted a riskier 'corner-cutting' strategy. Whilst these findings provide good evidence of older people being capable of adjusting their motor strategy to compensate for their level of motor skill and meet task demands (i.e. slowing down and reduced corner-cutting), it is not clear whether these results will generalise to real-life situations. The present chapter will therefore describe a similar experiment which again manipulated spatial and temporal constraints, but this time in a simulated driving environment. Driving was chosen both because of its likeness to the tracing task used previously (i.e. tracing wavy paths vs. driving along bending roads), and because driving is a critical motor skill.

The ability to remain mobile is undeniably an essential part of our independence. A driving licence is often regarded as symbolic of autonomy, providing freedom and self-reliance. It is therefore understandable that older people can view the prospect of giving up their right to drive in a negative light (Carp, 1971). Adverse consequences that have been associated with reduced frequency or cessation of driving in older adults include an increased risk of depression, more time spent at home and a decline in life satisfaction (Ragland, Satariano & MacLeod, 2005; Harrison & Ragland, 2007). The decision to stop driving itself is likely to fall on a spectrum. For example 84% of participants interviewed in Persson's (1993) study agreed that they stopped driving “at about the right time” (p. 89). While the exact reasons for cessation will vary on an individual basis, self-reported decisions broadly fit into two categories – (i) a gradual change in driving behaviour (e.g. less driving at night in order to compensate for physical problems, not driving with passengers, avoiding traffic), and (ii) major life events such as Stroke that lead to disability (Persson, 1993). Older drivers presenting with functional impairment (i.e. problems completing everyday tasks of daily living such as dressing) also report more driving difficulties (e.g. problems completing certain manoeuvres, dislike of night-time driving) and fewer hours spent on the road (Lyman, McGwin & Sims, 2001).

The fact that a decline in basic motor performance is associated with problematic driving and even cessation, calls for a greater understanding of how movement skills behind the wheel might be adversely affected by age. Such knowledge has implications both at a personal and societal level. Because people are living longer, it is important to keep older people mobile, for as long as possible. Nevertheless, it is also critical to ensure the roads remain a safe place for everyone, old and young. Accident statistics suggest that older people (≥ 75yrs) are involved in a higher number of fatal incidences per 100 miles driven when compared to younger (30-60yrs) drivers (Massie, Campbell & Williams, 1995). The underlying cause of road accidents is not always clear, though the Department for Transport Road Safety Research Report in 2009 stated that the most frequent types of crash where an older driver (>60 years) was considered partly to blame were ‘right of way violations’; collisions when carrying out manoeuvres such as lane changes, or turning on or off a road (Clarke, Ward, Truman & Bartle, DfT Road Safety Research Report 109, 2009). Identifying the driving strategies adopted by older drivers may therefore improve our understanding of road-safety issues

Little is currently known about steering behaviour in the older population. The following experiment therefore aimed to establish whether the spatial compensation observed in **Chapter 2** would translate to older adults' behaviour when driving along simulated roadways. Examining driving behaviour in a simulated environment provides the benefit of studying movement in a realistic scenario, while also allowing for precise control over the visual stimuli. The same shaped path that featured in the tracing task in **Chapter 2** was used as a basis to create a series of virtual roads. This allowed steering bias (i.e. the extent to which participant's cut-the-corner) and steering variability to be recorded as participants steered under conditions of varied road width and locomotor speed. Similar studies conducted in the past with younger adults have identified a tendency to "cut-the-corner" and therefore steer closer to the inside road-edge (i.e. take the 'racing line') (Mars, 2008; Robertshaw & Wilkie, 2008). Nevertheless, maintaining a more central road position would allow an older driver with increased motor variability to contain his or her trajectory within the constraints of the road boundaries. It was thus predicted that where possible, older participants would be more inclined to adopt a 'middle-of-the-road' strategy and exhibit less corner-cutting than the younger population. When external constraints (high speed) made a 'middle-of-the-road' compensatory strategy difficult to implement it was expected that errors in the older participants would increase.

3.2 Method

The following sections describe the methodology used to carry out the experiment. **Section 3.2.1** provides details of the participants recruited for the study and **3.2.2** describes how the simulated driving task was designed and implemented in the lab. The measures of steering performance that were recorded are defined in **Section 3.2.3**, along with methods of data analysis.

3.2.1 Participants

Twenty eight healthy individuals with no previous history of ophthalmological or neurological problems formed a second opportunistic sample (NB. participants included University of Leeds students and members of a local church, South Parade). Participants were split into two age groups. The young group (8 females, 6 males) were aged between 19 and 39 years (mean age = 24.07, *SD* = 5.28) and the older group (9 females, 5 males) were aged between 60 and 84 years (mean age = 71.86, *SD* = 7.01). All participants held a UK driving licence and considered themselves to be a driver (NB. Self-reported, see *Appendix B* for brief list of questions asked). The mean EHI score was 86.52 (*SD* = 21.25) indicating that all participants were right-handed. The Addenbrooke's Cognitive Examination Revised (ACE-R) (Mioshi, Dawson, Mitchell, Arnold and Hodges, 2006) was also administered to the older participants as a measure of basic cognitive ability. The average ACE-R score was 92.29 out of 100 (*SD* = 6.37) suggesting no sign of cognitive impairment (the cut-off for Dementia is 88/100). All participants gave their written informed consent, and the experiment complied with ethical guidelines approved by the University of Leeds ethical committee, in accordance with the Declaration of Helsinki.

3.2.2 Procedure and Apparatus

Participants were seated in a driving seat placed in front of a large screen (1.98m × 1.43m). The rotating, height adjustable, lockable chair allowed the older participants to comfortably transition into the chair. The distance from the eyes to the screen was 1m, and the distance from the eyes to the ground was 1.05m for all participants (Figure 3.1).

A realistic textured ground plane with superimposed road-edges was presented (similar to Wilkie & Wann, 2003b). The shape of the road was created using the following sum of sines formula:

$$x = \sin\left(\frac{z}{20}\right) + \sin\left(\frac{z}{15}\right) + \sin\left(\frac{z}{30}\right)$$

Figure 3.1 *An older adult participant steering along a road of medium (3m) width.*

The driving task was presented using a PC (Pentium(R) 4 CPU 3.20 GHz) to generate the scenes and a Sanyo Liquid Crystal Projector (PLC-XU58) to back-project the images. The edges of the road appeared in white against a grey gravel textured background with a blue sky (Figure 3.1). All roads followed the same shape but varied in width: narrow (1.5 m), medium (3 m) or wide (4.5 m). Speed of travel was constant within trials, but varied between trials so that each road type appeared five times at both a slow (8 m/s) and fast (16 m/s) speed. This resulted in a total of 30 roads to negotiate, which took around 10 minutes if the trials were completed without extended pauses. The order of conditions was randomised.

Participants were asked to steer along the virtual road and were told to *'stay within the boundaries'*. Steering was controlled using a force-feedback wheel (Logitech G27 with a 'return-to-centre' force active) and a 'paddle' button (positioned beneath their fingers) that allowed participants to control when a trial started (allowing rest between trials if needed). Driving simulators run the risk of inducing motion sickness and this was highlighted to participants during the consent process. Indeed, the majority of the older group did experience some motion sickness with 10 out of the 14 older participants experiencing nausea at some point in the experiment (compared to only 1 person in the young group).

3.2.3 Analysis

Three measures of steering performance were recorded: (i) steering error was calculated using the **Root Mean Square Error (RMSE)** of position from the middle of the road for each frame of each trial; (ii) In order to examine the variability of error across trials the **Standard Deviation of RMSE** (i.e. SD of steering error) was also calculated for each condition; (iii) the **Steering Bias** of position relative to the middle of the road indicated whether the participants cut-the-corner or were biased towards the outside edge. Larger positive values indicated more time spent steering towards the inside edge of the bend. Zero values do not, however, indicate that the participant stayed solely on the road midline (e.g. a participant could be highly variable but spend the same amount of time near the outside edge of the road as near the inside edge and so be unbiased). It is therefore important to examine bias alongside RMSE to fully evaluate steering performance. Trials in which RMSE exceeded 4m were treated as outliers and excluded from all analyses, but only five trials needed to be excluded in this way (three trials from the old group and two from the younger group with no more than one trial per participant excluded). Three mixed model ANOVAs were used to explore separately the steering performance measures (RMSE, SD of RMSE and steering bias). These analyses had a two (young and old age groups) × three (narrow, medium and wide roads) × two (slow and fast speeds) design. Where the Greenhouse-Geisser ε values are reported, the degrees of freedom were adjusted in order to account for sphericity.

3.3 Results

Figure 3.2a displays mean RMSE for the old and young groups on the narrow, medium and wide roads, for the slow and fast speed conditions. Table 3.1 also displays the ANOVA results. There was a main effect of locomotor speed (F (1, 26) = 93.06, p < .001, η^2_p = .78), road width (F (1, 26) = 41.47, p < .001, η^2_p = .62, ε = .77) and a significant speed × width interaction (F (2, 52) = 27.53, p < .001, η^2_p = .51). Errors were smallest on the narrow roads when steering at slower speeds, but higher speeds caused greater errors when the road was narrow. The age groups performed similarly in most conditions and there was no main effect of age (because of overlap the slow trials for young are hard to see in Figure 3.2a) but there was a width × speed × age interaction (F (2, 52) = 4.43, p < .05, η^2_p = .15). The three way interaction seems to be driven by the reduction in steering error between wide and narrow fast trials in the young (t (13) = 4.89, p<.001) but not for old (t (13) = .15, p=.89).

Root Mean Square Error (RMSE) provides a measure of within trial variability (relative to the road centre). Nevertheless, accurate control of steering depends upon a participant's ability to reliably reproduce actions. To examine how consistent the groups were in their steering across trials of the same type, the *SD* of RMSE was therefore examined. Figure 3.2b displays the mean *SD* of RMSE for the old and young groups on the narrow, medium or wide roads, in the slow and fast speed conditions. Table 3.2 also displays the ANOVA results, which revealed two significant effects. Firstly, there was a main effect of locomotor speed (F (1, 26) = 18.26, p < .001, η^2_p = .41), whereby steering was more variable when travelling quickly. This suggests that travelling at twice the speed made maintaining a consistent steering path across trials more difficult. Secondly, the older group were significantly more variable in their steering trajectories than the younger group (F (1, 26) = 6.67, p < .05, η^2_p = .20). Notably, the narrow/fast condition yielded the greatest difference between the age groups, suggesting that the older participants found this condition particularly challenging.

Table 3.2 also displays the ANOVA results for the steering bias measure. Participants generally cut corners (i.e. positive steering bias as shown in Figure 3.2c). Corner-cutting increased on the wider roads (F (2, 52) = 214.05, p < .001, η^2_p = .89, ε = .65) and when travelling at the faster speed (F (1, 26) = 62.23, p < .001, η^2_p = .71). A significant interaction between road width and locomotor speed (F (2, 52) = 50.61, p < .001, η^2_p = .66, ε = .64) showed that the higher speed had a greater influence on steering bias when the road was narrow (Figure 3.2c). The difference in steering bias between the slow and fast conditions on narrow roads was 0.27m, whereas on medium and wide roads the difference was 0.13m and 0.07m respectively. A significant between-subjects effect of age revealed that the older participants were less likely to cut corners than the young (F (1, 26) = 6.67, p < .05, η^2_p = .20). The only exception to this pattern may have been when steering along the narrow road at a fast speed (mean bias for young and old: 0.47m and 0.48m respectively) which was when the older participants struggled to maintain their accuracy (as measured by RMSE) and were also highly variable (shown by *SD* of RMSE).

Table 3.1 *The effect of road width and locomotor speed on the Root Mean Square Error of steering error (RMSE) in old and young participants. Where the Greenhouse-Geisser ε values are reported, the degrees of freedom were adjusted in order to account for sphericity.*

	RMS Steering Error				
	F	df	η^2_p	ε	p
Road Width (RW)	41.47	2, 52	.62	.77	<.001 **
Speed (S)	93.06	1, 26	.78		<.001 **
Age[a] (A)	.26	1, 26	.01		.617
W * A	2.86	2, 52	.10		.08
S * A	.03	1, 26	.03		.38
S * W	27.54	2, 52	.51		<.001 **
S * W * A	4.43	2, 52	.15		.02 *

[a]Age was the only between-subjects factor.

*Result significant at the p < .05 level.

**Result significant at the p < .001 level.

Table 3.2 *The effect of road width and locomotor speed on Steering Bias and variability (SD of RMSE) in old and young participants. Where the Greenhouse-Geisser ε values are reported, the degrees of freedom were adjusted in order to account for sphericity.*

	SD of RMSE					Steering Bias				
	F	df	η^2_p	ε	p	F	df	η^2_p	ε	p
Road Width (RW)	.87	2, 52	.32	.65	.381	214.05	2, 52	.92	.65	<.001 **
Speed (S)	18.26	1, 26	.41		<.001 **	62.23	1, 26	.71		<.001 **
Age[a] (A)	6.67	1, 26	.20		.016 *	6.67	1, 26	.20		.016 *
RW * A	.51	2, 52	.12	.62	.518	.89	2, 52	.06	.65	.378
S * A	1.81	1, 26	.07		.190	.69	1, 26	.03		.415
S * W	.32	2, 52	.03	.68	.379	50.61	2, 52	.70	.64	<.001 **
S * W * A	.45	2, 52	.02	.68	.566	20.82	2, 52	.09	.64	.174

[a]Age was the only between-subjects factor.

*Result significant at the $p < .05$ level.

**Result significant at the $p < .001$ level.

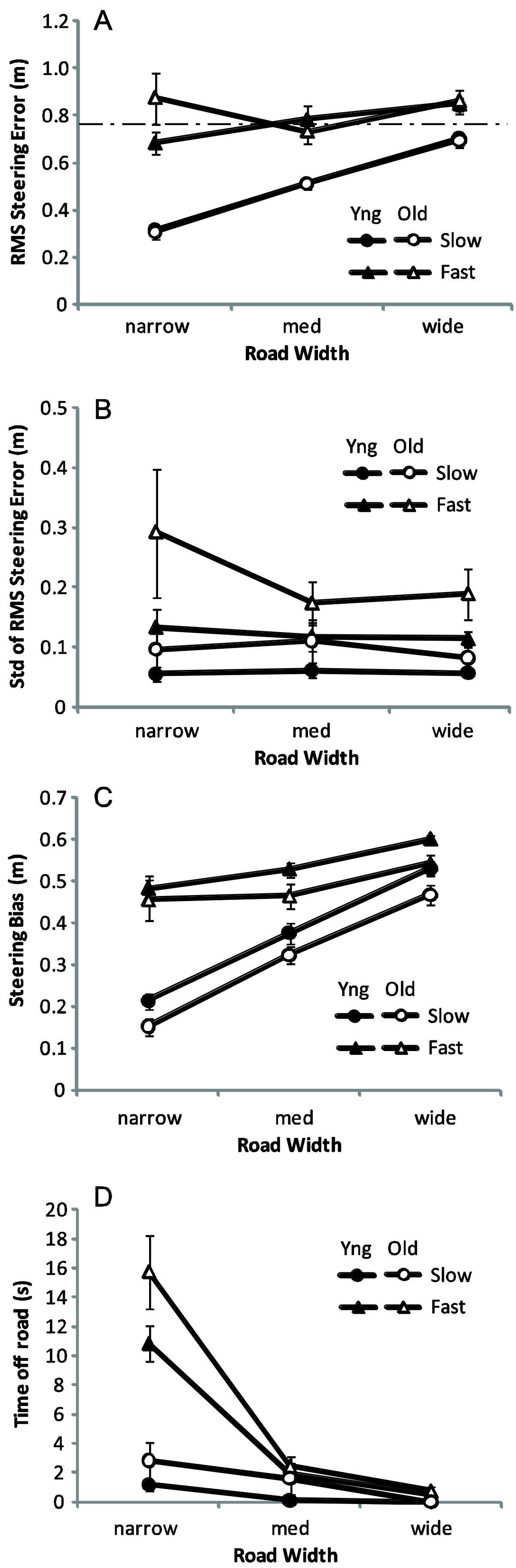

Figure 3.2 (caption overleaf)

Figure 3.2 *(p. 58) Steering performance on the narrow (1.5m), medium (3.0m) and wide (4.5m) roads at the slow (circles) and fast (triangles) speeds for young (filled symbols) and old (open symbols) groups:* ***(A)*** *Root Mean Square Error (RMSE), where a larger value indicates that trajectories were further from the path midline. The horizontal dot/dashed line indicates the distance of the narrow road edges from the midline (0.75m)* ***(B)*** *Mean SD of RMSE, where a larger value indicates less consistent steering trajectories across trials.* ***(C)*** *Mean Steering Bias, where a larger positive value indicates trajectories passed closer to the inside of each bend.* ***(D)*** *Total time (s) spent off the road in each condition averaged across Young or Old participants. Bars = Standard Error of the Mean.*

Figure 3.3 *(p. 60)* ***(A)*** *Sinusoidal roads of three possible widths: narrow (1.5 m, blue), medium (3 m, green) and wide (4.5 m, red). The grey box shows the section of road that is expanded in the remaining panels. For clarity only the widest (red) road edges are shown in panel's B-E.* ***(B)*** *Individual steering trajectories for a representative young participant on narrow (blue), medium (green) or wide (red) roads at slow speeds or* ***(C)*** *fast speeds. This young participant scored close to the mean group steering bias (mean steering bias = 0.47 m; group mean = 0.46 m).* ***(D)*** *Individual steering trajectories for a representative old participant on narrow, medium or wide roads at slow speeds or* ***(E)*** *fast speeds. This old participant scored close to the mean group steering bias (mean steering bias = 0.38 m; group mean = 0.40 m).*

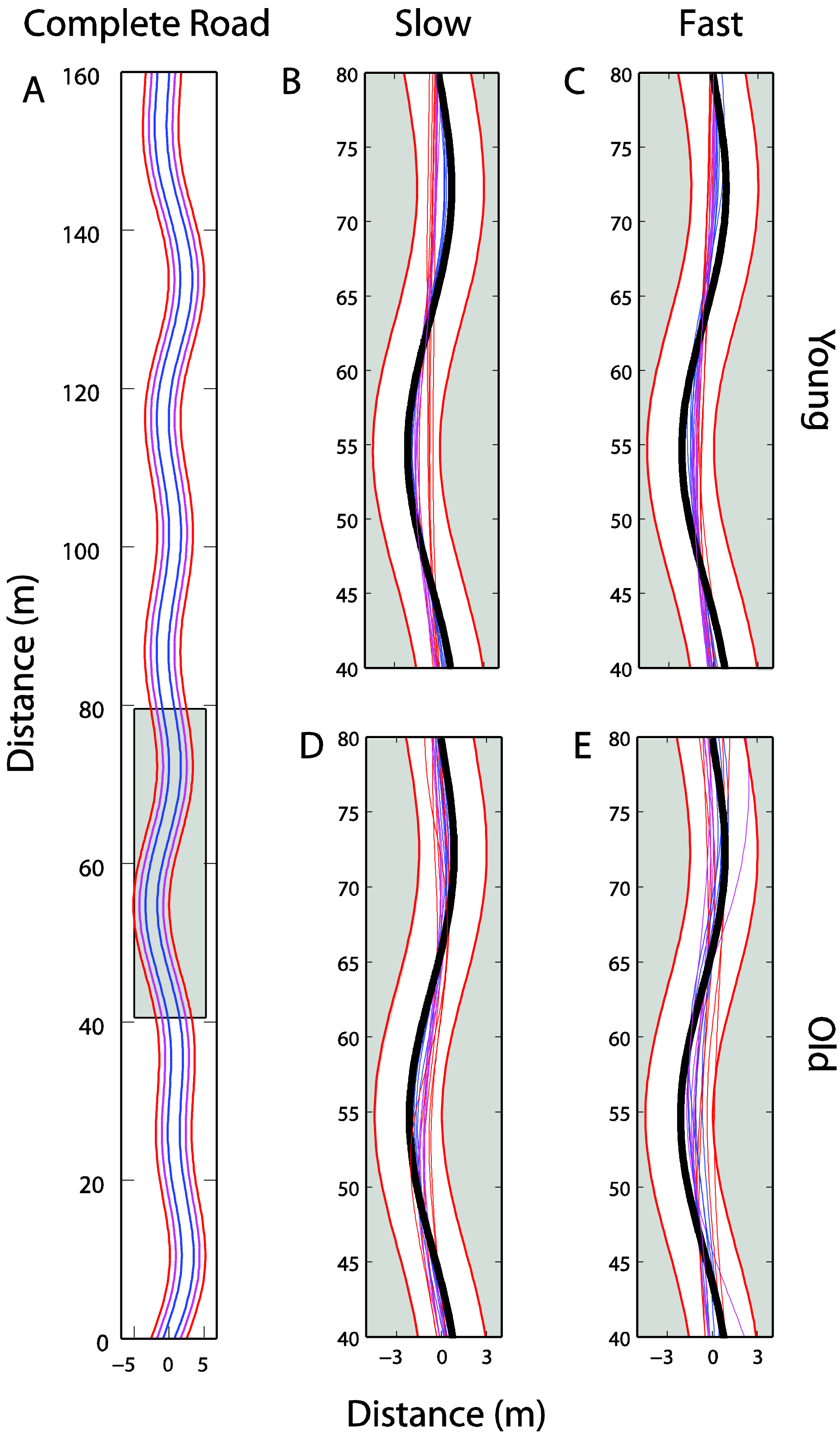

Figure 3.3 (caption on previous page)

Looking across the measures it seems that the narrow/fast condition was the most difficult to complete successfully (i.e. by staying on the road) and the old in particular struggled with this width/speed combination. It should also be noted that apart from the narrow/fast condition, the older adults performed at similar levels of RMSE to the young, whilst exhibiting less steering bias. The old were therefore not merely avoiding cutting corners because they valued accuracy more highly (i.e. they were no more accurate than the young). Rather, it seems that the old adopted a more central position in order to stay on the road, which was relatively successful unless the conditions were particularly difficult.

Overall, the steering results show that the older participants were more variable in their steering compared to the young (i.e. greater SD of RMSE), but corner-cutting was less prevalent (i.e. lower steering bias scores).When calculating the length of time participants spent off the road (Figure 3.2d), the younger group were found consistently capable of taking the ‘racing-line’ trajectories that passed close to the inside road-edge, yet with no increased risk of leaving the road. The same statistical pattern was found for time spent off road as for the other steering measures: a main effect of path width, locomotor speed, and an interaction between width and speed (respectively F (2, 52) = 63.87, p < .001, ε = .61; F (1, 26) = 64.58, p < .001; F (2, 52) = 45.82, p < .001, ε = .70). The only difference was that the main effect of age did not reach statistical significance (F (1, 26) = 3.52, p = .072). This was examined further by plotting individual steering trials for one young (Figure 3.3b&c) and one old participant (Figure 3.3d&e). The young participant stayed closer to the middle of the road when travelling slowly on the narrower roads (blue & green lines on Figure 3.3b) than on the wide road (red lines on Figure 3.3b), but clearly corner-cutting increased for thinner roads when travelling more quickly (Figure 3.3c). The older participant showed greater variability in the trajectories taken, especially at the fast speed (Figure 3.3e), consistent with the measure of SD of RMSE. But the older participant followed the shape of the road more closely; this is most evident on the wide road at slow speeds (compare the red lines in Figure 3.3b and 3.3d).

3.4 Discussion

The experiment in **Chapter 2** identified a tendency for older adults to slow their movements down and keep the stylus closer to the path midline in a task that required them to trace paths of variable thickness at different speeds. This suggests that older people are sensitive to their level of skill, and are capable of adjusting their movement strategy to meet task demands. The aim of the present chapter was to examine whether this pattern of behaviour would generalise to a 'real-life' motor task by analysing accuracy, precision and bias in a simulated driving scenario.

Previous comparisons of hand-writing and walking movements demonstrate that general patterns of behaviour can be observed during both actions (Hicheur et al., 2005). It was therefore hypothesised that older adults would adopt a more central road position compared to the young, who typically cut-the-corners when steering (Mars, 2008; Robertshaw & Wilkie, 2008). A comparable set of conditions to the tracing task in **Chapter 2** was used in order to generate virtual roads of different widths, which steered along at a set slow or fast locomotor speed. As expected, the patterns of behaviour found previously did seem to transfer from tracing to steering, with similar effects of path width and locomotor speed on spatial strategy. Steering at faster speeds along wider roads yielded a greater degree of corner-cutting, as shown by measures of steering bias and Root Mean Square Error (RMSE). Further to this, calculations of steering variability (SD of RMSE) revealed more variable trajectories across all road widths and speeds in the older group. These findings may help to explain anecdotal reports that older drivers have a spatial bias towards the road centre. A middle-of-the-road strategy reduces the risk of crossing a road edge (just as keeping the nib of the pen close to the middle of the path can prevent error in tracing tasks). The compensatory steering strategy adopted by our older participants therefore seems appropriate given the greater variability observed in some conditions. This result also complements the findings of Trommershäuser et al. (2005), which suggests that the human nervous system is able to optimise actions by minimising the costs based on the variability present in the system. The following two sections (**3.4.1** and **3.4.2**) consider the implications of these findings in the real-world.

3.4.1 Real-life Compensation

The finding that older people ‘play it safe’ compared to their younger counterparts is in line with research that suggests older drivers are more risk adverse in real-world situations. When comparing the nature of road accidents associated with old and young drivers, qualitative differences become apparent which imply heightened risk aversion within the older population (Anstey, Wood, Lord & Walker, 2005; McGwin & Brown, 1999). In McGwin and Brown’s (1999) report, accidents involving young drivers were frequently a result of risk-taking behaviours such as drunk driving, whereas older drivers were more likely to be involved in accidents associated with fatigue, early/late night driving, travelling at high speeds or bad weather. Furthermore, older drivers were found to be over-represented in accidents characterised by difficulties with the perceptual-motor aspects of driving (e.g. failure to yield, heed stop signs/signals, attend to objects/people/vehicles, pull out at the correct time at intersections, turn or change lanes appropriately) suggesting that their greater incident rate is more to do with a decrease in skill as opposed to risk-taking behaviours and/or decisions. An older driver’s reluctance to drive in these potentially hazardous situations could reflect an awareness of the threat that age-related motor decline poses to driver safety. Accordingly, the research implies that older drivers might implement a compensatory strategy of ‘avoidance’ whereby they steer clear of risky driving situations (e.g. rush hour, night-time driving), or a strategy of ‘adjustment’ whereby they modify their driving style to account for their difficulties (e.g. by reducing speed; Hakamies-Blomqvist, Mynttinen, Backman & Mikkonen, 1999; Horberry, Hartley, & Gobetti et al., 2004; Planek & Overend, 1973). Our findings reflect the latter method of compensation – a tendency to adjust steering movements in order to avoid error in light of heightened motor variability. Hence, older participants adjusted their position on the road to compensate for a decrease in their ability to maintain a consistent path. In real-life situations, older drivers also tend to compensate by slowing down (Garber & Gadirau, 1988). In our experiment, speed was kept constant (within trials) so that steering behaviour could be directly compared across age-groups, but it is likely that the spatial and temporal compensations interact within real world driving tasks. For instance, an older driver might slow down on a narrow road to decrease his/her path variability and/or allow them to avoid the need to cut corners. Nevertheless, our data show clearly that when these strategies are prevented because of external constraints (e.g. being in a stream of fast moving traffic) then the age-related deficits in skill become apparent. This finding has implications for the assessment of the older driver.

3.4.2 The Costs of Compensation

Compensatory strategies are not without cost. In the real world, a reduced consistency in road position makes it more difficult for the driver behind to safely complete manoeuvres that rely on the stability of the leading vehicle’s road position (e.g. overtaking and merging). Likewise, driving too slowly increases the variance in the speed of vehicles travelling together which increases the risk of accidents (Garber & Gadirau 1988). Slow driving can frustrate other drivers leading to risky overtaking manoeuvres (McGwin & Brown 1999). It therefore seems that older drivers’ compensatory strategies may not always be sufficient to ensure road safety. It is also important to note that the use of the word ‘strategy’, both in reference to the first and second experiment, does not imply that the compensatory behaviour is a conscious decision. There may indeed be a tendency for older adults to consciously and strategically compensate for their difficulties. However, more fundamental adaptations that are not cognitively penetrable might also result from the increased variability of signals within the aged nervous system (Desrosiers et al., 1995; Krampe, 2002; Smith et al., 1999; Verkerk et al., 1990). The human nervous system appears to be sensitive to noise in the informational variables used to carry out skilled tasks such as reaching (Tresilian, Mon-Williams & Kelly, 1999), grasping (Ernst & Banks, 2002) and steering (Wilkie & Wann, 2002) with less reliable information being down-weighted. Thus, the bias towards adopting a particular spatial position might reflect low-level perceptual-motor adaptations to noise within the system. In older adults, such noise is likely to be introduced both through degraded visual inputs and impaired motor outputs. In our experiments, all participants reported normal (or corrected-to-normal) vision. However, without conducting extensive eye-examinations, it was not possible to identify whether decrements in individual motor performance were caused primarily by visual impairments (though all participants signed a statement claiming they were free of ‘ophthalmological problems’). The relatively homogenous behaviour of the older adults suggests that noise in the system was not solely due to visual problems. In fact, because the older adults experienced a greater degree of motion sickness in the present experiment, it might be that they were particularly reliant on visual information. Following the curvature of the road requires larger changes in steering trajectory and results in a greater degree of rotation in the optic flow field. The steering strategy adopted by older adults (i.e. to follow the shape of the road) may therefore have led to elevated reports of motion sickness. Nevertheless, because a similar pattern of behaviour was observed in the tracing task discussed in **Chapter 2**, where no motion sickness issues were reported, it is highly unlikely that the age differences reported here can be explained by this phenomenon.

3.4.3 Conclusions

The findings of the experiment in this chapter reveal for the first time; age differences in steering bias and variability, which may be informative in terms of maintaining road safety. Specifically, it is important to establish what strategies are adopted by older drivers in order to ensure their own personal safety, along with the safety of other road users. The extent to which compensatory strategies preserve road safety is unclear, but the high crash rate for older drivers suggests that strategic compensations are not completely successful. Moreover, whilst there is evidence that compensatory strategies might help prevent accidents (De Raedt & Pondjaert-Kristoffersen, 2000) compensation is not always possible without incurring a cost. Hakamies-Blomqvist (1994) argued that avoiding potentially hazardous scenarios leaves a driver less able to cope when presented with an unavoidable situation. Likewise, compensating through speed reduction has a cost since it makes merging with motorway traffic difficult (De Waard, Dijksterhuis, & Brookhuis, 2009) and the further a vehicle's speed deviates from the average on a motorway, the greater the risk of accident (Garber & Gadirau, 1988). In the present study, it was shown that the older group found it particularly difficult to steer down the narrow road at fast speeds and this was the only condition in which they exhibited similar amounts of corner-cutting to the young. Subsequently, it can be seen that the system will fail to compensate when put under pressure, placing the driver and other road users in danger.

3.4.4 Implications for Future Work with KineLab

The patterns of movement identified in **Chapter 2** using a KineLab tracing task were successfully replicated in a simulated driving environment. This provides good evidence that KineLab is an effective tool for measuring age differences in motor performance in the lab, and that it can identify patterns of movement that generalise to movement in the real-world. The decision was therefore made to design and implement further visuomotor tasks using the KineLab system. Benefits of KineLab include the fact that the equipment is portable, which is useful for testing older adults who can find transport difficult and who prefer to be examined at home. The tablet PC used to run KineLab is also familiar to most participants (i.e. most people have used a computer before), and it does not cause any unpleasant side-effects (i.e. high rates of motion sickness reported in older adults during driving simulation).

Chapter 4
Age Differences in Manual Asymmetries

4.1 Introduction

The previous two chapters examined whether older adults would adjust their movements in order to compensate for motor decline. In one experiment, participants used their preferred (right) hand to trace paths under different temporal/spatial constraints (**Chapter 2**), and in another experiment (with comparable constraints), participants used both hands to steer along virtual roads in a simulated driving environment (**Chapter 3**). While these studies provide good insight into the effects of ageing on bimanual and unimanual performance in the preferred hand, it is also important to consider the outcome when the non-preferred, hand is used. This is particularly important when investigating how an individual with motor decline (e.g. older adults, stroke patients), might compensate for experienced difficulties. In the general population, while most people will be able to state a preference towards using the right or left hand to complete motor tasks, many activities actually involve the use of both hands (e.g. washing up, getting dressed, holding the hair-drier while coming your hair). How motor decline can affect the hand that is used less often is therefore of interest, given the role it plays in vital bimanual skills. The present chapter therefore explores the effects of ageing on manual asymmetries – the differences between preferred and non-preferred hand performance.

Handedness, the preference towards using either the right or left hand when completing motor tasks, is established in early childhood and is presumed to be maintained throughout life. Accordingly, studies with children and younger adults have reported manual asymmetries in the past (e.g. Fagard, 1987; Truman & Hammond, 1990; Culmer et al., 2009). The fact that older adults have had decades of practice with the preferred hand, might suggest that they should therefore exhibit large motor asymmetries, perhaps even to a greater extent than when young. Ageing is, however, associated with changes in motor performance whereby movements become slower and less accurate over time (Desrosiers et al., 1995; Verkerk et al., 1990; Morgan et al., 1994; Pohl et al., 1995; Welsh et al., 2007). It is presently unclear whether this decline in motor performance alters the propensity toward motor asymmetries seen in younger adulthood.

At the neurological level, motor asymmetry can be explained by lateralisation of brain function (i.e. one hemisphere being predominant in a specific function). Nevertheless, the ageing brain appears to show greater bilateral patterns of activation, especially during cognitive processes (a phenomenon termed ‘HAROLD’; Hemispheric Asymmetry Reduction in Older Adults). The HAROLD model (Cabeza, 2002) is based on neurophysiological evidence which shows reduced asymmetry between dominant and non-dominant hemisphere activation in older adults when completing cognitive tasks (e.g. episodic and semantic memory encoding and retrieval, and inhibitory response). For example, during episodic memory encoding and retrieval, increased PFC activity is observed in the left hemisphere during encoding and in the right hemisphere during recall in the younger population; whereas in older groups there is a greater bilateral pattern of activation throughout both parts of the task (Cabeza et al., 1997). Furthermore, bilateral patterns of activation are associated with better performance in the old, which suggests that HAROLD may serve a compensatory purpose (Cabeza et al., 2002).

If reduced asymmetry of function is evident for a range of different cognitive processes (i.e. if HAROLD is not task-specific), it is likely that the phenomenon may be generalised to other brain regions and tasks. This might include sensory-motor processes that occur outside of the PFC. In line with this, recent functional imaging research has indicated an age-related reduction in lateralisation in the temporal and parietal areas (Grady et al., 2002). Moreover, increased bilateral activation in motor regions has been found when older adults perform basic motor tasks such as finger-tapping and button-pressing (Sailer et al., 2000; Calautti, et al., 2001; Mattay et al., 2002; Ward & Frackowiak, 2003; Naccarato et al., 2006; Heuninckx et al., 2005; Heuninckx et al., 2008). The idea of HAROLD being a compensatory mechanism in the motor domain has also been suggested in a study by Heuninckx et al., (2008), which identified a positive correlation between performance on an interlimb coordination task (i.e. moving the hands and feet at the same time) and bilateral motor cortical activation in older adults. The greater the extent of overactivation, the better older adults performed, especially in the most difficult task condition (i.e. moving the hands and feet in the opposite direction).

One explanation for age-related increases in bilateral activation in older adults is that transcallosal inhibition, which usually ensures ipsilateral deactivation of primary motor cortex in the young, may be reduced in the ageing brain (Ward & Frackowiak 2003; Peinemann et al., 2001). Nevertheless, findings of reduced lateralisation in the old seem to be somewhat task dependent, as both motor sequence learning (Daselaar et al., 2003) and cued simple movements (Fang et al., 2005) do not appear to exhibit age-related cortical reorganisation. Rowe, Sibner and Filipovic et al. (2006) used low-frequency Repetitive Transcranial Magnetic Stimulation (rTMS) and Positron Emission Tomography (PET) to study age-related changes in neural connectivity. It was found that older adults exhibited increased movement-related activation of PM bilaterally during a button pressing task, and that this cortical region was also more susceptible to the inhibitory effects of rTMS in the old. Rowe et al. (2006) did not, however, report a general loss of lateralisation of frontal cortical specialization (as would be expected based upon the HAROLD model; Cabeza, 2002) but (as they highlighted) their measures may have lacked the requisite sensitivity to detect changes in the motor system.

Whilst there are now a number of studies that show age-differences in lateralisation of cortical activity, to date, there are few studies that have examined age-related motor asymmetries in skilled behavioural tasks. One skilled action that has been examined previously is the efficiency of reaching movements, where there do appear to be reduced asymmetries in older adults (Przybyla et al., 2011). The coordination of reaching movements is usually superior in the preferred arm (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2002), but Przybyla et al. (2011) found that in older adults these asymmetries were reduced. One possibility is that ageing leads to reduced asymmetries simply because of a greater impairment to the most skilled (preferred) hand. The results showed, however, that young participants tended to overshoot leftwards of the target when using their non-preferred hand, the older participants produced straighter trajectories that were similar to those shown by the preferred hand (in both age groups). Furthermore, there was no difference in accuracy between the arms in the older group, whereas the young were more accurate when using their preferred arm. Another particularly elegant study has also investigated visuomotor adaptation during reaching movements, and found that older adults showed a similar degree of interlimb transfer after adaptation for both left and right arms, whereas adaptation mainly occurred between the preferred to non-preferred arm in the young (Wang et al., 2011). Such reduced asymmetries would support the idea that interhemispheric inhibition declines with increased age.

Evidence for reduced motor asymmetries in older adults performing gross motor reaches is an interesting and important empirical observation, especially in light of the well-documented support for HAROLD in the cognitive domain. The findings of Przybyla et al. (2011), Wang et al. (2011) and the HAROLD model clearly predict that the normal manual asymmetries found in younger adults should be absent in older adults. The following thus examines these predictions using a task that is almost a canonical example of motor asymmetries – the fine visuomotor task of holding a pen within the hand to trace a shape. This task yields a large degree of lateralisation in younger groups and captures many critical aspects of skilled motor performance (Culmer et al., 2009). Interestingly, large manual asymmetries have been observed in both young and older adults when drawing circles within a series of square boxes (Teixeira, 2008). This task, however, required participants to complete the boxes from right to left with the left hand, and vice-versa with the right hand. The asymmetries in drawing time for each hand may, therefore, have been purely due to task differences as it has been shown that there are costs involved with moving both the preferred and non-preferred hand in the opposite direction to that used when writing (Johnson et al., 2010).

In this study, hand performance was compared in a task that required participants to trace along a complex path shape that varied in thickness. Whereas Przybla et al. (2011) controlled speed, participants in this experiment were told that their line must not leave the path, but they must also try to complete the task as quickly as possible (i.e. no specific temporal constraint). One path was sufficiently thin to ensure that the task had to be completed by tracing the path's shape precisely. Thicker paths were also used where the task could be completed more quickly by 'cutting-the-corners' (a behaviour previously observed in **Chapter 3**). To explore age differences in manual asymmetries, participants were asked to complete the task once with their preferred (right) and once with their non- preferred (left) hand. Age and hand differences in speed and accuracy, as well as a measure of overall performance efficiency (the 'Speed Accuracy Cost Function', SACF) were then examined.

4.2 Method

Participant details are provided in **Section 4.2.1**, and **Section 4.2.2** describes how the tracing task was designed in KineLab. Outcome measures of interest, and methods for analysis, are outlined in **Section 4.2.3.**

4.2.1 Participants

Thirty seven individuals with no history of ophthalmological or neurological problems were recruited (NB. participants recruited from Coulby Newham Community Centre and Teesside Musical Theatre Company). All participants were also right-handed as indexed by average score on the EHI of 90.53

(*SD* = 13.66). Participants were split into two age groups. The young group consisted of 20 participants (12 females, 8 males) aged between 18 and 31 years (mean age = 25.5, *SD* = 5.66) and the old group comprised 17 people (11 females, 6 males) aged between 62 and 79 years (mean age = 69 years, *SD* = 4.46). The University of Leeds' ethics and research committee approved this study, and all participants gave written, informed consent in accordance with the Declaration of Helsinki.

4.2.2 Procedure and Apparatus

A tracing task was designed in KineLab (Culmer et al., 2009) that required participants to trace a complex path shape. Using the same apparatus as detailed in **Chapter 2** (**Section 2.2.2)**. Participants used a handheld stylus to trace paths which were the same shape (see Figure 4.1) but varied in thickness (4mm, 9mm, 14mm). Each path thickness condition was presented five times in a randomised order (hence a total of 15 paths, with the random order different for every participant). The paths measured 166.42mm in height from top to bottom, and 131.72mm in width from left to right. Given that the thinnest condition was only 4mm thick, corner-cutting was not a feasible strategy when tracing the thin paths. Even when tracing centrally, it would only leave a 1.5mm gap either side of the nib, thus making it particularly difficult to avoid crossing outside of the path boundaries when the path was thin. Participants completed the task twice; once with their preferred (right) hand, and once with their non-preferred (left) hand. The order of hand use was counterbalanced across all groups so that half of the participants started with their preferred hand and half with their non-preferred hand. The following instructions were provided; *"follow the path from start to finish as quickly as possible. You must NOT go outside of the path"*. Participants were also asked to not touch the screen with anything other than the pen (jewellery was removed and sleeves were rolled up).

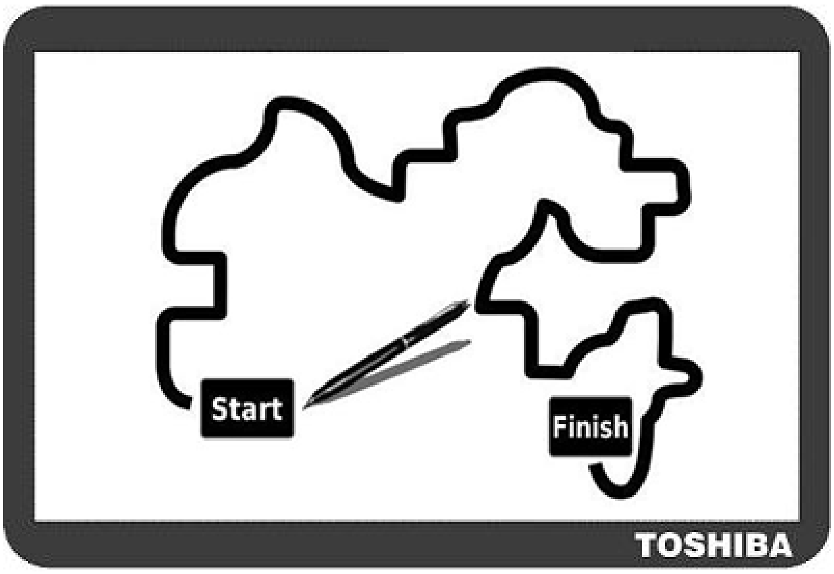

Figure 4.1 *Path shape as it appeared to participants in the 'thin' condition.*

4.2.3 Analysis

Three measures of tracing performance were recorded. First, **Movement Time (MT)** indicated the time taken (s) from tracing onset to trial completion. Second, **Shape Accuracy (SA)** was determined by matching the path made by the participant (i.e. the input path) with the reference path (i.e. the centre of the path displayed in the task) using a 'point-set registration' technique. Point-sets were generated for the input and reference paths by discarding temporal information and re-sampling the X and Y coordinates at a spatial resolution of 1mm using linear interpolation. A robust point-registration method (Myronenko & Song, 2010) was then used to determine the rigid transformation that best transformed the input path to match the reference path. Shape Accuracy was then calculated by evaluating the mean distance between points in the transformed input path and the reference path. This measure was extremely useful as it gave a metric of accuracy (i.e. indicating the extent to which participants remained within the path boundaries and the deviation from the shape of the path). Finally, movement duration and accuracy were also considered together as a composite measure. The

Speed Accuracy Cost Function (SACF) is calculated by multiplying SA by MT to provide an overall measure of task performance, with higher scores indicating poorer performance. This measure has been found to distinguish reliably between preferred and non- preferred hand performance in the past (e.g. Culmer et al., 2009).

The occasional spurious extreme value needed to be excluded from the data-set due to erroneous recording of the touch screen (e.g. accidental touching with the sleeve or arm). At most, one of the five trials per path thickness condition was lost, but no more than one trial per participant. Only five trials were excluded from the data collected from the preferred and non-preferred hand. After removing extreme values, participants' median scores (i.e. MT. SA and SACF) on the three path thickness conditions were calculated for the preferred and non-preferred hand data. A separate mixed model ANOVA was then carried out for each outcome measure (hand × path thickness × age).

4.3 Results

Because participants were free to trade off speed and accuracy, a composite measure of movement efficiency was calculated (MT × SA) whereby a larger number indicates worse performance (i.e. the Speed Accuracy Cost Function; SACF). The ANOVA on SACF (Table 4.1 and Figure 4.2) revealed significant interactions between hand and age (F (1, 35) = 8.09, p <.05, η^2 =.19), path thickness and age (F (2, 45) = 8.53, p <.05, η^2_p =.20), and most importantly between hand, path thickness and age (F (2, 60) = 11.35, p < .001, η^2_p =.25). The older participants were significantly worse than the young (F (1, 35) = 19.81, p < .001, η^2_p =.36) and showed a greater decline in performance (i.e. an increase in SACF) from the thicker to thinner path condition, but seemed to perform equivalently with both hands. To test this formally, a posthoc t-test was carried out on the SACF data for the thin path condition in the older group, and there was no significant difference between the hands (t (16) = 1.9, p >.074). In contrast, the young performed significantly worse with their non-preferred hand than with their preferred hand when tracing the thin paths (*t* (19) = 4.0, $p < .001$), though non-preferred hand performance in the young was still better than in the old (*t* (35) = 3.29, $p < .05$).

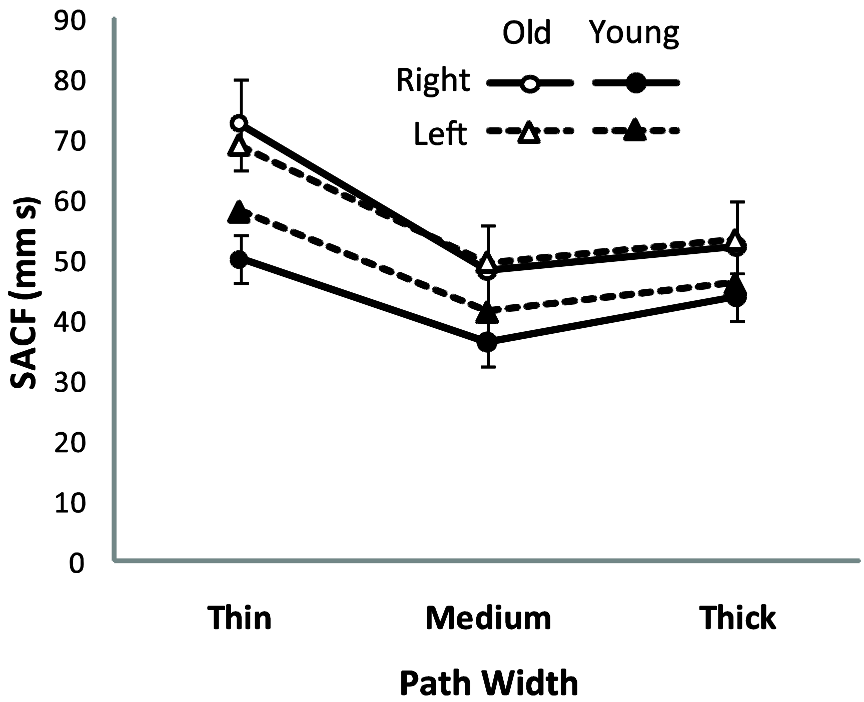

Figure 4.2 *Mean Speed Accuracy Cost Function (mm s) for the young (filled symbols) and old (open symbols) groups on the narrow, medium and thick paths when using the dominant (bold lines and circles) and non-dominant (dashed lines and triangles) hand. Bars = Standard Error of Mean.*

Table 4.1 *<u>Speed Accuracy Cost Function (SACF)</u>: The effect of Hand (preferred or non-preferred) and Path Thickness (Thin, Medium, Thick) in old and young participants. Greenhouse-Geisser ε values are reported where degrees of freedom were adjusted to account for sphericity.*

	SACF (mm s)				
	F	*df*	η^2_p	*ε*	*p*
Hand	5.59	1, 35	.14		.024 *
Path Thickness (PT)	148.14	2, 70	.81	.63	<.001 **
Age[a]	19.81	1, 35	.36		<.001 **
Hand × Age	8.09	1, 35			.007*
PT × Age	8.53	2, 70	.20	.63	.003 *
Hand × PT	1.11	2, 70	.03	.85	.329
Hand × PT × Age	11.35	2, 70	.25	.85	<.001 **

[a]Age was the only between-subjects factor.
*Result significant at the *p* < .05 level.
**Result significant at the *p* < .001 level.

A possible reason for finding no differences between performance in the two hands for the old using the SACF measure is that both MT and SA are changing by equal and opposite amounts – the non-preferred hand is slower but more accurate, so performance looks similar across both hands. Nevertheless, Figure 4.3b and 4.3d demonstrate that this was not the case, with similar MT and SA performance for both hands clearly evident in the older group. This was examined formally with an ANOVA on the MT data (see Figures 4.3a and 4.3b), which revealed a three-way interaction between hand, path thickness and age group (see Table 4.2; F (2, 70) = 4.50, $p < .05$, η^2_p =.11). Participants took longer when using the non- preferred hand (F (1, 35) = 6.29, $p < .05$, η^2_p =.15), but when examining performance on thin paths this increase was only significant for the young (t (19) = 3.1, p = 0.006) and not the old (t (16) = 0.4, p = 0.694). Movement Time did increase as the path became thinner (F (2, 70) = 494.09, p < .001, η^2_p =.85) showing that participants were slower to complete the paths in the thin condition, but there were no significant interactions found between hand and age, or path thickness and age (see Table 4.2).

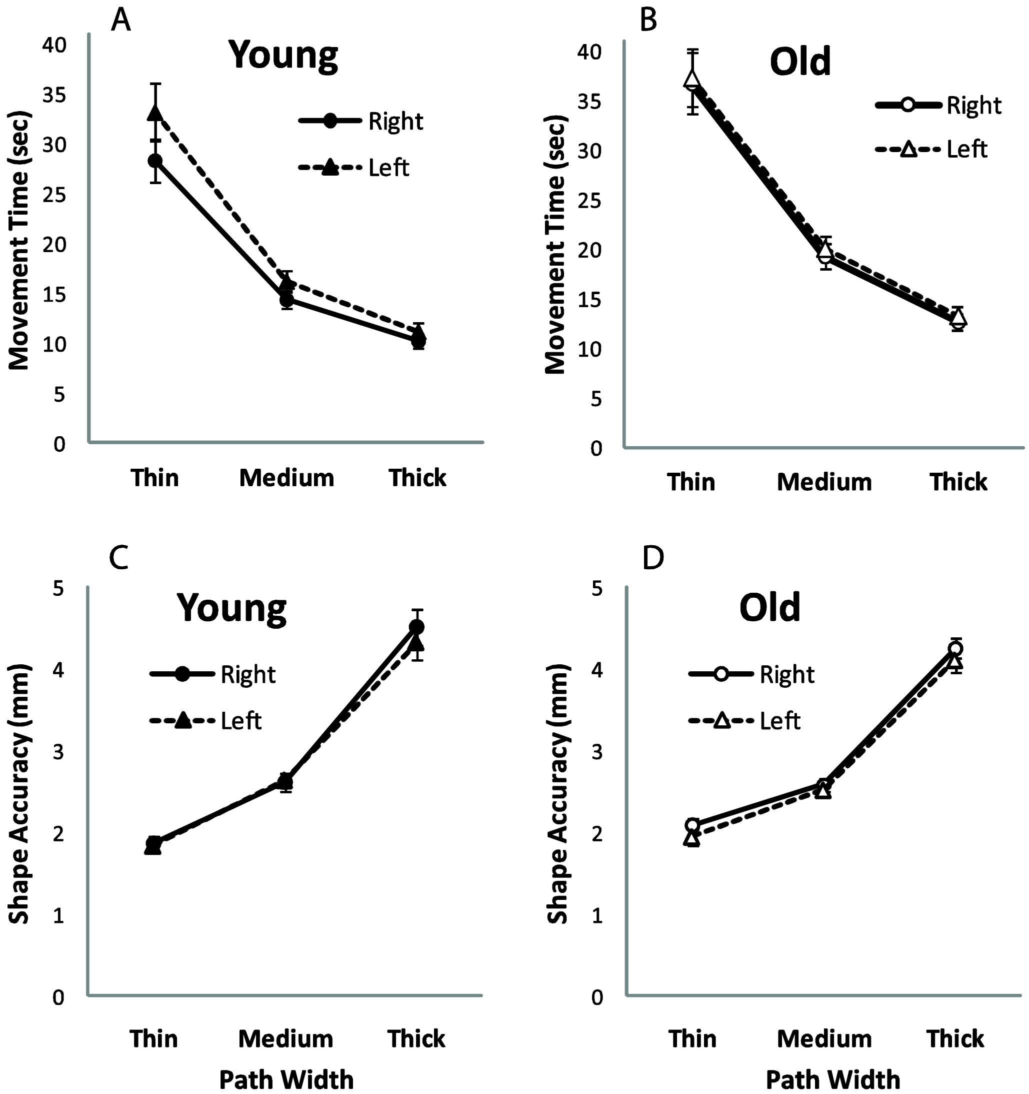

Figure 4.3 *Performance for young (filled symbols) and old groups (open symbols) on the thin, medium and thick paths using the preferred hand (solid lines and circles) and non-preferred hand (dashed lines and triangles).* ***(A)*** *Movement Time (s) for the young group****;(B)*** *Movement Time (s) for the old group;* ***(C)*** *Shape Accuracy (mm) for the young group;* ***(D)*** *Shape Accuracy (mm) for the old group. Bars = Standard Error of Mean.*

Table 4.2 *Movement Time (MT): The effect of Hand (preferred or non-preferred) and Path Thickness (Thin, Medium, Thick) in old and young participants. Greenhouse-Geisser ε values are reported where degrees of freedom were adjusted to account for sphericity.*

	MT (s)				
	F	*df*	η^2_p	*ε*	*p*
Hand	6.29	1, 35	.15		.017 *
Path Thickness (PT)	193.41	2, 70	.85	.51	<.001 **
Age[a]	4.66	1, 35	.12		.038 *
Hand × Age	2.00	1, 35			.17
PT × Age	1.48	2, 70			.23
Hand × PT	4.11	2, 70	.11	.61	.042 *
Hand × PT × Age	4.50	2, 70	.11	.61	.033 *

[a]Age was the only between-subjects factor.
*Result significant at the $p < .05$ level.
**Result significant at the $p < .001$ level.

The analysis of SA showed that corner-cutting increased as the path became thicker (F (2, 70) = 494.09, p < .001, η^2_p =.93), but there was no main effect of age, no significant interactions between hand and age, or between path thickness, hand and age (see Table 4.3). This pattern suggests that both the young and old prioritised accuracy equally with each hand. There was, however, an interaction between path thickness and age (F (2, 70) = 3.27, $p < .05$, η^2_p =.09) which is indicative of reduced accuracy by the young on thick paths. This finding is consistent with behaviour observed in the previous two chapters, whereby younger adults were more likely to cut-the-corners when tracing or steering (see **Chapters 2** and **3**). Overall the analyses of MT and SA confirm the original SACF analysis that the old performed similarly with both hands, whereas the young were more proficient when using their preferred hand.

Table 4.3 *Shape Accuracy (SA): The effect of Hand (preferred or non-preferred) and Path Thickness (Thin, Medium, Thick) in old and young participants. Greenhouse-Geisser ε values are reported where degrees of freedom were adjusted to account for sphericity.*

	SA (mm)				
	F	*df*	η^2_p	*ε*	*p*
Hand	3.11	1, 35			.086
Path Thickness (PT)	493.86	2, 70	.93	.58	<.001 **
Age[a]	0.10	1, 35			.75
Hand × Age	0.29	1, 35			.59
PT × Age	3.28	2, 70	.09		.044 *
Hand × PT	3.23	2, 70	.08	.78	.059
Hand × PT × Age	1.08	2, 70			.35

[a]Age was the only between-subjects factor.
*Result significant at the $p < .05$ level.
**Result significant at the $p < .001$ level.

4.4 Discussion

This experiment examined movement time and shape accuracy in old and young participants when tracing paths of varied thickness with each hand, and then calculated a composite measure of overall motor performance (Speed Accuracy Cost Function; SACF). The data confirmed that while the young showed clear manual asymmetries, these differences disappeared in the older group. The asymmetries in the young seem to have been mainly driven by faster movement times for the preferred hand, especially when tracing the thin paths (see Figure 4.2a). In contrast, for the older adults there were no differences in speed or accuracy of tracing movements for either hand. This suggests that when an older adult is given an equivalent task to perform with his/her non-preferred hand to preferred hand, they perform equivocally with both hands.

The purpose of the experiment was to subject the predictions of the HAROLD model (Cabeza, 2002) to an extreme test. The HAROLD hypothesis, which is based on findings of reduced asymmetries when older adults perform cognitive tasks (Cabeza et al. 1997), would imply that older people should also show less of a difference in motor skill between the preferred and non-preferred hand. The findings of this study seem to support this prediction, and are also consistent with previous empirical reports of reduced manual asymmetries in older adults found in the motor domain (Przybyla et al., 2011; Wang et al., 2011). An alternative explanation for the present findings could be, however, that the older adults adopted a highly conservative strategy whereby they moved at a low baseline speed that allowed them to meet the accuracy requirement of the task with either hand. This proposal effectively suggests that the older participants were not tailoring their behaviour to the task. Nevertheless, the fact that the old adjusted their movement speed as a function of path thickness clearly shows that they were able to adapt their motor behaviour based on task demands. Hence the data appear in this case to support the suggestion of reduced hemispheric function asymmetry.

A reduction in hemispheric asymmetry has been linked with greater bilateral patterns of brain activity during cognitive tasks (Cabaza et al., 1997) as well as basic motor tasks (Sailer et al., 2000; Calautti et al., 2001; Mattay et al., 2002; Ward & Frackowiak, 2003; Heuninckx et al., 2005; Naccarato, et al., 2006; Heuninckx et al., 2008). Calautti et al. (2001) found overactivation in right-side motor regions in a group of right-handed older adults who were required to produce repeated thumb-to-index-tapping movements. Similarly, Mattay et al. (2002) suggested that the older brain seems to recruit additional motor regions, which are not activated in younger groups, even during a very basic button-pressing task. A bilateral pattern of brain activity in older adults was also linked to better performance, since older participants who did not show the same degree of bilateral activation had longer reaction times. A similar outcome was also observed in Heuninckx et al.'s fMRI (2008) study. This suggests that reduced hemispheric asymmetry may serve a compensatory purpose whereby older people engage the assistance of additional brain regions, which younger people do not require, in order to maintain a better level of performance. Furthermore, in past research, older participants have been found to produce trajectories with their non- preferred hand that were similar to the preferred hand in both age groups (Przybyla et al., 2011). The present experiment does not match these previous findings. Though the older adults showed no differences in performance between their two hands, they performed at a lower level than seen in the non-preferred hand of the young. When the data was examined to see whether those adults with less asymmetry performed better, there were no clear links found between degree of lateralisation and performance on any measure. One possibility is that it would have been necessary to increase the constraints over movement time (e.g. Przybyla et al., 2011) to push the performance of the older adults nearer to their limits, in order to detect a relationship between performance and asymmetry.

Reports of reduced hemispheric asymmetry in the motor domain have a wider application to the growing literature in support of the HAROLD hypothesis. Thus far, the majority of research into age differences in hemispheric asymmetry has focused on the higher-level cognitive processes of the PFC (i.e. the basis of the HAROLD model). Nevertheless, emerging evidence of age-related reductions in manual asymmetry at both the behavioural and neurophysiological level provides support for the generalisation of HAROLD to brain regions outside of the frontal cortex. The findings of the present experiment suggest that similar reduced asymmetries may be expected in the brain regions associated with the control of fine motor actions. This would certainly concur with past demonstrations of reduced functional asymmetries identified in the motor cortex of older adults during performance of simple motor tasks (Sailer et al., 2000; Calautti et al., 2001; Mattay et al., 2002; Ward & Frackowiak, 2003; Heuninckx et al., 2005; Naccarato, et al., 2006; Heuninckx et al., 2008). What is presently unclear though is whether an age-related reduction in manual asymmetries can be expected across all types of movement. At the neurophysiological level, age differences in functional asymmetries do not extend to some motor tasks; for example, implicit motor sequence learning and cued simple movements (Daselaar et al., 2003; Fang et al., 2005). Furthermore, there are behavioural studies that have shown comparable manual asymmetries between old and young participants, and in some cases even an increase in older adult asymmetries, across a range of different motor tasks (Mitrushina et al., 1995; Chua et al., 1995; Francis & Spirduso, 2000; Teixeria, 2008; Goldstein & Shelly, 1981; Weller & Latimer-Sayer, 1985; Dolcos et al., 2002; Chua et al., 1995). This conflict in findings implies that the extent to which manual asymmetries are identified in any given experiment may depend on task design and how performance is measured. Asymmetries will be less apparent on easier tasks where the non-preferred hand is likely to match the performance of the preferred hand, and an inappropriate choice of outcome metric could also mean that asymmetries manifest in other aspects of performance are overlooked. This issue is particularly important when studying older adults because they often adjust their movements differently to the young, in order to meet task demands (**Chapters 2** and **3**; Morgan et al., 1994: Welsh et al., 2007).

The hypothesis that manual asymmetries are task-specific and sensitive to measurement clearly warrants further empirical investigation, especially with regards to the practical implications of the finding of reduced asymmetries in older adults. For example, the impact of a stroke might be less dependent than previously thought on whether the damage is ipsilateral or contralateral to the preferred hand. The observation of reduced asymmetries also implies that there may be benefits to switching to use the non-preferred limb when the preferred limb is affected by an age-related condition such as arthritis. Accordingly, the next chapter explores the issue of measurement when studying manual asymmetries, with the primary aim being to ‘tease out’ the extent to which the HAROLD phenomenon can be applied to the motor domain.

Chapter 5

Getting the Measure of Manual Asymmetries in Older Adults

5.1 Introduction

Most humans have a strong phenomenological sense that one of their hands is superior to the other hand when carrying out many motor tasks (e.g. writing, throwing a ball). It therefore seems reasonable to assume that the measurement of manual dexterity will reveal differences between the two hands of most individuals. But is this a safe assumption? In **Chapter 4** of this thesis, the idea that manual asymmetries vary with age was explored using a tracing task. While the young demonstrated superior performance when using their preferred hand to trace paths, the old group showed no manual asymmetries. A possible explanation for this finding is a decrease in functional asymmetry in the ageing brain. Research in the cognitive domain has recently yielded the 'HAROLD' hypothesis (Cabeza, 2002) which suggests that brain activity becomes more bilateral, possibly as a means of compensation, with increasing age. If HAROLD were to be generalised to the areas of the brain that are responsible for movement, this could therefore explain a reduction in asymmetries in the motor domain. On the other hand, an alternative hypothesis is that manual asymmetries are much more subtle than widely presumed and are therefore highly sensitive to conditions of measurement (Teixeria, 2008). Accordingly, this chapter considers the role of task design in the assessment of manual asymmetries, with the aim being to identify whether reduced manual asymmetries in older adults is dependent upon the type of task and outcome metric chosen to measure motor performance. **Section 5.1.1** of the introduction begins with an overview of past research that has examined age differences in manual asymmetries both at the neural and behavioural level. **Sections 5.1.2** and **5.1.3** respectively consider the influence of task design and metric choice when measuring differences between the hands.

5.1.1 Previous Observations of Age Differences in Manual Asymmetries

We tend to develop a preference towards using the right or left hand to complete motor tasks during childhood, and then maintain that preference throughout life. Many studies with young adults have hence reported superior performance of the preferred hand across a range of motor activities (e.g. Fagard 1987; Truman & Hammond 1990; Culmer et al., 2009). But is the preferred hand always better?

Our current understanding of how manual asymmetries change with age is limited, and given the overwhelming evidence for an age-related decline in general motor performance (examples include Cooke et al., 1989; Pratt et al., 1994; Verkerk et al., 1990; Morgan et al., 1994; Desrosiers., 1995; Pohl et al., 1995; Contreras-Vidal et al., 1998), it seems possible that old age might lead to differential changes in the abilities of the preferred and non-preferred hands. For example, older people could become increasingly dependent on using the preferred hand due to many years of practice (and feedback). Alternatively, discrepancies between the hands could diminish as we age as a consequence of neurological change, specifically in hemispheric lateralisation (e.g. Cabeza, 2002).

The hypothesis that suggests that alterations in the distribution of neurological activity will alter behavioural patterns is an idea that has been predominantly explored in the cognitive domain. HAROLD (Cabeza, 2002) is a model based on the reduced lateralisation of cortical activation observed in the aging brain, and predicts an increased bilateral pattern of neural activity when older adults complete cognitive tasks (e.g. tasks involving inhibitory responses, memory encoding and retrieval). The underlying basis of increased bilateral activation is not certain, but it could be linked with reduced transcallosal inhibition (Przybyla et al., 2011). The fact that reduced hemispheric asymmetry in older adults is sometimes associated with better performance in these tasks has been taken as evidence that the HAROLD phenomenon may serve a compensatory purpose (e.g. Cabeza et al., 1997;

Cabeza et al., 2002; Przybyla et al., 2011). If the mechanisms underlying HAROLD are global changes in cortical inhibition then it might be expected that manual asymmetries would also be affected, i.e. reduced lateralisation of motor function where asymmetries in function (both at the level of neurons in the motor cortex and in the action itself) would reduce in older age. This hypothesis has gained considerable attention over recent years; however the evidence varies greatly in the nature and extent of age-related differences found in hemispheric lateralisation, and the degree of manual asymmetries identified in motor tasks.

Neurophysiological studies of older adults have found reduced hemispheric asymmetry in the motor cortex and the recruitment of additional brain regions during finger-tapping, button-pressing and hand-grip tasks (Sailer et al., 2000; Calautti et al., 2001; Mattay et al., 2002; Ward & Frackowiak, 2003; Heuninckx et al., 2005; Naccarato, et al., 2006; Heuninckx et al., 2008), yet this does not extend to implicit motor sequence learning or cued simple movements (Daselaar et al., 2003; Fang et al., 2005). Behavioural studies present conflicting results, with age-related reductions in manual asymmetries varying across studies. In some experiments, older adults display reduced asymmetries in reaching, visuomotor adaptation and fine motor control (e.g. **Chapter 4**; Przybyla et al., 2011; Wang et al., 2011). There are also studies, however, that have reported no age differences in asymmetries on some motor tasks (e.g. Mitrushina et al., 1995; Chua et al., 1995; Francis & Spirduso, 2000; Teixeria, 2008), or even an increase in older adult asymmetries compared to the young (e.g. Goldstein & Shelly, 1981; Weller & Latimer-Sayer, 1985; Dolcos et al., 2002; Chua et al., 1995; Teixeria, 2008). Such variability across studies strongly suggests that the 'HAROLD' phenomenon is not something that can be generalised to all motor behaviour.

5.1.2 The Role of Task Design

An alternative explanation for the conflict in findings within the existing behavioural literature could be that asymmetries relate to the underlying characteristics of the chosen motor tasks. Manual asymmetries are likely to be more subtle than might be expected at a phenomenological level; possibly due to structural learning (i.e. a generalised learning effect whereby mastering a skill with one hand will allow a high level of performance in the other hand). The theory of structural learning suggests that the human nervous system acquires general rules that can be applied when controlling actions with similar dynamics. A canonical example is using a variety of bicycles when learning to ride – general rules about the control dynamics of the action are learned and later aid skill acquisition in novel but physically related situations (e.g. Braun et al., 2009). Johnson et al. (2010) recently examined structural learning by measuring performance of the preferred and non-preferred hand in Western-educated individuals when tracing shapes leftwards versus tracing shapes rightwards. Tracing performance was found to be better when moving in the conventional Western handwriting direction (i.e. rightwards) for both the preferred and non-preferred hands, and in both the right-handed and left-handed participants. These results provided strong evidence of structural learning and can explain why learning to write with the preferred-hand takes years, whilst it takes only weeks to subsequently train the non-preferred hand to an equivalent level of performance (e.g. Walker & Henneberg, 2007).

The theory of structural learning would imply that absolute differences between the hands could be relatively small. Thus, asymmetries may only become apparent when participants are pushed to the very limits of their performance capacity, a threshold which will inevitably vary both across individuals and between groups. If the task is too difficult then it will be hard to differentiate the preferred and non-preferred hands (i.e. both hands will show a floor effect). If the task is not difficult enough, both hands will perform at a ceiling level. In both cases, differences between the hands will be hard to detect. Hence the measurement of asymmetries may require tasks that are in the ‘Goldilocks zone‘(i.e. not too easy or too difficult, but just right), whereby a sufficient level of complexity is present to demonstrate the superior performance of the preferred hand, without being so difficult that neither hand can perform well.

5.1.3 The Role of Metric Choice

In order to observe asymmetries, the correct choice of outcome measure to index motor performance is also essential. The majority of studies that have examined age differences in manual asymmetries thus far have used measures which have combined performance speed and accuracy (i.e. resulting in a single overall score for performance), or have only measured movement speed (e.g. Francis & Spirduso, 2000; Chua et al., 1995; Weller & Latimer-Sayer, 1985; Goldstein & Shelly, 1981; Mitrushina et al., 1995; Mattay et al, 2002). Relying solely on one outcome measure could mean that these experiments failed to identify asymmetries that were manifest in other aspects of performance. This is particularly important when examining age differences, given that older adults make both temporal and spatial adjustments to their movements in order to meet task demands (see **Chapters 2, 3** and **4**; Morgan et al., 1994: Welsh et al., 2007).

5.1.4 Experimental Aims

It seems then that the reduction in manual asymmetries sometimes observed in older adults may not be a result of reduced hemispheric asymmetry, but could instead reflect task differences. To examine this possibility the following two experiments were designed to record different measures of motor performance in younger and older adults across a range of motor tasks. While Experiment One addressed issues related to task-specificity, Experiment Two addressed compensatory trade-offs and the implications they have for the measurement of manual asymmetries.

5.2 Experiment One

The following sections contain the method (**5.2.1**), results (**5.2.2**) and brief discussion (**5.2.3**) for Experiment One, which examined age differences in manual asymmetries using a battery of motor tasks. This allowed asymmetries to be tested under a number of different measurement conditions including tracking, aiming and tracing tasks, that each varied in degree of spatial and temporal constraint.

5.2.1 Method

This section provides participant details (**Section 5.2.1.1**), a description of the KineLab task battery with rationale for the chosen outcome metrics (**Section 5.2.1.2**) and methods for data analysis (**Section 5.2.1.3**).

5.2.1.1 Participants

Eighty five healthy individuals with no previous history of ophthalmological or neurological problems formed an opportunistic sample (NB. young participants recruited from the University of Leeds and University of Leeds Chaplaincy and older participants from South Parade Baptist Church). Participants were grouped by age. The young group (33 females, 34 males) were aged between 18 and 40 years (mean age = 23.59, *SD* = 4.68) and the old group (10 females, 8 males) were aged between 60 to 83 years (mean age = 70.89, *SD* = 4.95). All participants were right-handed as indexed by the average EHI score of 97.72 (*SD* = 7.47) out of the maximum 100. The mean EHI score for the old was 99.44 (*SD* = 2.36) and for the young 97.26, (*SD* = 8.28). All participants gave their written informed consent, and the experiment complied with ethical guidelines approved by the University of Leeds ethical committee, in accordance with the Declaration of Helsinki.

5.2.1.2 Procedure and Apparatus

KineLab (Culmer et al., 2009) was used to design a battery of three different motor tasks. The apparatus used was the same as described previously in **Chapter 2** (**Section 2.2.2**) whereby participants used a handheld stylus to complete the tasks which were delivered in succession on a tablet PC (see Figure 5.1c). Instructions for the tasks were also integrated into the test battery for continuity. All participants completed the battery once using their preferred (right) hand and once using their non-preferred (left) hand. This was counterbalanced so that every other participant began with their non-preferred hand. The tasks were as follows;

(i) *Manual Tracking:* Participants were instructed to keep the stylus on a green dot that moved around the screen in a figure-of-eight pattern (dot diameter = 10mm). The speed of the dot progressed from a slow pace whereby it took 16s to complete one figure-of-eight, to a medium (time = 8s), and fast (time = 4s) pace respectively. Each speed condition repeated three times before increasing to the next speed, resulting in a total of nine figure-of-eights to track (see Figure 5.1a). Immediately after these trials, participants followed the same instructions but with the spatial pattern visible throughout (a line drawn figure-of-eight shape, height = 110mm; width = 55mm; see Figure 5.1b). This task required participants to match the changing spatial location of the target. **Root Mean Square Error (RMSE)** was therefore chosen as the outcome variable, as it provides a single metric of performance accuracy. Root Mean Square Error (mm) is the average distance of the stylus from the closest reference point in the centre of the figure-of-eight path. A higher RMSE value therefore indicates reduced accuracy.

(ii) Aiming: Participants were instructed to move the pen as quickly as possible from one green dot (diameter = 10mm) to another as each one appeared on the screen (distance between dots = 117mm). The appearance of the dots followed the shape of a pentagram which repeated 10 times (5 moves per repetition) (see Figure 5.1d). As this task required participants to move from one fixed position (of defined spatial accuracy) to another at a rapid pace, decreasing movement duration was the challenge of the task. Accordingly, **Movement Time (MT)**, the time taken to move the stylus between two dots, was calculated across all of the aiming movements and the mean MT used as the measure of performance (i.e. where higher MT indicates reduced performance).

(iii) Tracing: Participants were required to trace a complex path (height = 166mm; width = 132mm; thickness = 4mm) from start to finish whilst trying to remain within the section of the path highlighted by a translucent box. The box changed position in steps to progress around the path (a change every 5s), in order to enforce a steady pace and constrain the MTs of participants. There were six trials which featured two versions of the path, the second version being a

mirror-image of the first path, which appeared every other trial (see Figure 1e). Because MTs were controlled, **Shape Accuracy (SA**) was used as a measure of performance accuracy. SA was calculated by taking each traced path and calculating the difference in comparison to a given reference path that marked the exact centre of the displayed path. This was achieved using an automated ‘point-set registration’ technique (Myronenko & Song, 2010) that is described in more detail in **Section 4.2.3** of this thesis. Higher SA values indicate greater deviation from the reference path, and hence reduced accuracy*.*

Figure 5.1 *Screen shots taken from the KineLab motor task battery in Experiment One (NB. not to scale) which included Manual Tracking without* ***(A)*** *and with* ***(B)*** *a spatial pattern, Aiming* ***(D)****, and Tracing* ***(E). (C)*** *Older adult completing the Manual Tracking Task (with spatial pattern).*

5.2.1.3 Analysis

Mixed model ANOVAs were used to examine the effects of age and hand on the mean scores for the outcome measures recorded in each task (RMSE, MT and SA). For the Aiming and Tracing tasks the mean scores across all trials were calculated, and separate ANOVAs applied. Further specifics on the analysis for the Manual Tracking data are detailed in **Section 5.2.2.** For all analyses, Greenhouse-Geisser estimates of sphericity (ε) are reported where degrees of freedom have been adjusted.

5.2.2 Results

The following sections provide the results of data analyses for the Manual Tracking (**5.2.2.1**), Aiming (**5.2.2.2**) and Tracing (**5.2.2.3**) tasks. **Section 5.2.2.4** also addresses the issue of individual differences in manual asymmetries across the dataset.

5.2.2.1 Manual Tracking

An initial analysis of RMSE across all factors showed that there was no interaction between the presence of the figure-of-eight spatial pattern and the hand used (preferred or non-preferred). To simplify reporting of the findings, data was therefore averaged across the two Manual Tracking Tasks (with and without spatial pattern), which revealed an identical pattern of findings for the remaining factors. Tracking became less accurate as the speed of the dot increased (F (2, 166) = 1361.80, p < .001, η^2_p = .94, ε = .62). Older participants were less accurate than the young (F (1, 83) = 94.01, p < .001, η^2_p = .53), with a significant speed × age interaction highlighting a disproportionate effect of task difficulty on accuracy in the older group (F (2, 166) = 72.22, p < .001, η^2_p = .47, ε = .81). Accordingly, it can be seen in Figure 5.2 (which displays mean RMSE for the old and young in the slow, medium and fast speed conditions) that accuracy scores in the old group moved further away from the scores achieved by the young as dot speed increased (i.e. the difference in mean RMSE between the old and young in slow condition = 2.16mm; medium = 7.26mm; fast =10.27mm). Crucially there was no significant main effect of hand and no hand × age, speed × hand, or speed × hand × age interactions (all p > 0.05).

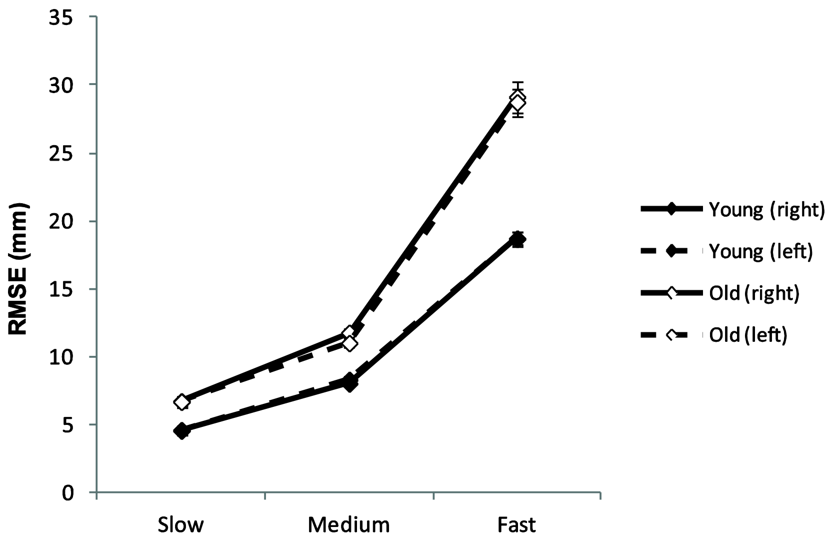

Figure 5.2 *Mean Root Mean Square Error (mm) in the Manual Tracking Tasks of Experiment One, for the non-preferred left (dashed lines) and preferred right (solid lines) hand in the old (open symbols) and young (filled symbols) groups. Larger RMSE values indicate reduced accuracy. Bars = Standard Error of the Mean.*

5.2.2.2 Aiming

The ANOVA for MT in the Aiming Task established a between-participant effect of age, whereby the old were slower than the young (F (1, 83) = 67.32, p < .001, η^2_p = .45). A main effect of hand also revealed manual asymmetries (F (1, 83) = 6.14, p < .05, η^2_p = .07), with participants producing faster aiming movements when the preferred hand was used. There were, however, no hand × age, speed × hand or speed × hand × age interactions (all p > 0.05).

5.2.2.3 Tracing

The Tracing Task applied both spatial and temporal constraints on movement. The analysis for the SA measure showed that the old were less accurate (F (1, 83) = 39.19, p < .001, η^2_p = .32), with higher SA scores than the young (mean SA for old = 1.19mm; mean SA for young = 0.89mm). Manual asymmetries were also identified (F (1, 83) = 23.46, p < .001, η^2_p =

.22) whereby tracing was more accurate when the preferred hand was used. There were no significant interactions between hand × age, speed × hand or speed × hand × age (all $p > 0.05$).

5.2.2.4 Individual Differences in Manual Asymmetries

One possible limitation of the methods used to describe manual asymmetries so far is that they do not explain the degree to which individual differences influence the findings. Whilst the preferred hand was superior in some individuals (i.e. faster or more accurate) there were also cases where the preferred hand was actually worse. To examine the extent to which old and young participants conformed to expected asymmetries (i.e. better performance when using the preferred hand) an 'asymmetry value' was calculated between hands for each person in each task (i.e. performance for the preferred hand subtracted from the non-preferred hand). Figure 5.3 shows the proportion of young and old participants that produced the expected asymmetries across the outcome measures during the Manual Tracking, Aiming and Tracing tasks. Despite the fact that both age groups were classed as right-handed (i.e. mean EHI score for old = 99.44, *SD* = 2.36; mean EHI score for young = 97.26, *SD* = 8.28), not all participants demonstrated superior performance when using their 'more-skilled' hand. In the Manual Tracking Tasks even though there were no significant hand asymmetries revealed in the ANOVA, 44% of the young participants and 50% of the old participants were more accurate when using the preferred hand (mean RMSE for preferred hand = 13.18mm, *SD* = 0.27; mean RMSE for non-preferred hand = 13.01mm, *SD* = 0.30). In contrast, despite significant differences between preferred and non-preferred hands in the ANOVAs, 22% of the young and 39% of the old did not show the expected MT asymmetries in the Aiming Task (mean MT for preferred hand = 1.37s, *SD* = 0.03; mean MT for non-preferred hand = 1.41s, *SD* = 0.03), and 15% of the young and 28% of the old did not demonstrate the expected SA asymmetries in the Tracing Task (mean SA for preferred hand = 0.09mm, *SD* = 0.03; mean SA for non-preferred hand = 1.10mm, *SD* = 0.03). It seems then, that despite strong hand preferences (i.e.as indexed by EHI), there were large individual differences in the extent of manual asymmetries exhibited. While all participants were indexed by the EHI as strongly right-handed, one possible explanation for the individual differences in manual asymmetries could be that those participants with a weaker preference for the right hand (i.e. lower EHI scores), were also those who showed smaller asymmetries. To examine this further, a test of correlation was used to investigate whether there was a relationship between magnitude of asymmetries exhibited by participants and their degree of hand-preference. Nevertheless, no significant correlations were found for RMSE in Manual Tracking (r (85) = -.100, p = 0.362), MT in Aiming (r (85) = 0.001, p = 0.994) or SA in Tracing (r (85) = -.148, p = 0.178).

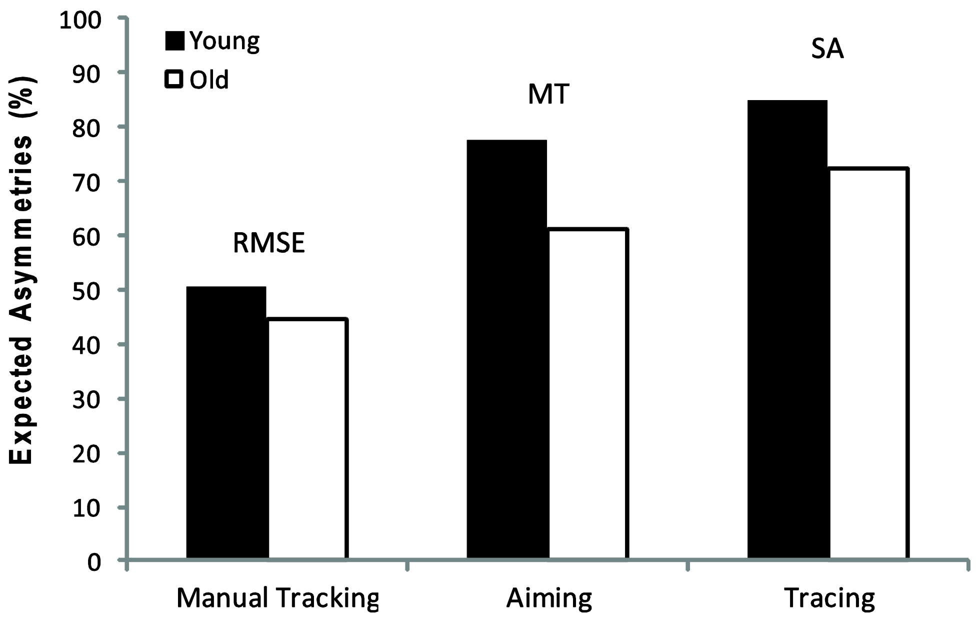

Figure 5.3 *Proportion of young (black bars) and old (white bars) participants that showed manual asymmetries in the expected direction (preferred hand performing better) on measures of motor performance recorded during Experiment One. For the Manual Tracking task, the combined RMSE values from both versions of the Manual Tracking Task (with and without spatial pattern) were averaged across the slow, medium and fast speed conditions. For Aiming and Tracing tasks the difference between the preferred and non-preferred hand were calculated for Movement Time (MT) or Shape Accuracy (SA) respectively.*

5.2.3 Discussion

Age differences in motor performance were prevalent across all tasks. Older participants were less accurate when Tracking, especially when demands were high (i.e. faster speeds); they took longer in the Aiming Task, and showed a greater deviation from the 'ideal' reference path when Tracing. The critical question, however, was whether older adults would exhibit reduced manual asymmetries compared to the young. This was not the case, as very similar patterns of behaviour emerged for both young and old groups. In the Manual Tracking Task neither group exhibited consistent hand asymmetries, whereas there were clear hand asymmetries when Aiming and Tracing.

These data therefore do not support the hypothesis that one consequence of the HAROLD model is reduced asymmetries in motor performance; as such a mechanism would predict reduced asymmetries regardless of task. Instead, these data support the hypothesis that differences between the preferred and non-preferred hand are relatively small (i.e. because mastering a skill involves learning the dynamical structure – a form of learning that benefits both hands), and asymmetries vary in magnitude as a consequence of task demands. Detecting these differences therefore requires (i) that tasks push both hands to perform at a high level of capability, and, (ii) that there is careful selection of the appropriate outcome metric. The latter is especially difficult if participants trade-off one aspect of performance (e.g. spatial accuracy) for another (e.g. speed). Experiment Two explores this issue of compensatory trade-offs in more detail.

5.3 Experiment Two

This section provides the method (**5.3.1**), results (**5.3.2**) and brief discussion (**5.3.3**) for Experiment Two, whereby a similar tracing task was used as previously described in **Chapter 2**, to examine manual asymmetries under different levels of temporal and spatial constraint (see **Section 2.2.2**). The tasks used in the test battery of Experiment One (tracking, aiming and tracing) did not allow comparisons to be made between varied spatial and temporal constraints within the same task. For example, the aiming task allowed participants to trace at their own speed, but there was no spatial restriction on how the route participants were to take when moving the pen between dots (they were just instructed to do it ‘quickly and accurately’). Furthermore, the tracing task imposed a temporal restriction, as participants had to keep their tracing within a moving frame, but again with no variation on the thickness or shape of the path. Hence in this experiment both the temporal and spatial components were explicitly controlled.

5.3.1 Method

This section gives participant details (**Section 5.3.1.1**), a description of the tracing task with chosen outcome metrics (**Section 5.3.1.2**), and details on the method of data analysis (**Section 5.3.1.3**).

5.3.1.1 Participants

A new opportunistic sample was recruited, comprising twenty four right-handed individuals with no history of ophthalmological or neurological problems (mean EHI = 97.71; *SD* = 4.82). Eleven participants (8 female, 3 males) aged between 18 and 32 years formed the young group (mean age = 24.18, *SD* = 4.24), who were recruited from Aker Solutions Global Engineering Company, and 13 participants (9 female, 4 males) aged between 61 and 75 years formed the old group (mean age = 69.08, *SD* = 3.10), who were recruited from the local community in Stockton-On-Tees. The University of Leeds ethics and research committee approved this study and all participants gave written, informed consent in accordance with the Declaration of Helsinki.

5.3.1.2 Procedure and Apparatus

Three dynamic tracing tasks were created using KineLab (Culmer et al., 2009), which required participants to draw a line along paths that were presented on a tablet PC using a handheld stylus (i.e. same apparatus as used in Experiment One, **Section 5.2.1.2**). Each path was the same shape (height top to bottom = 184.3mm; width left to right = 19.8mm), but varied in thickness (2mm, 4mm, 6mm) to manipulate spatial constraints. The timing of the task was also precisely controlled in order to examine behaviour under different temporal restraints. A constant speed was set by asking participants to trace within two horizontal red bars (spaced 250mm apart) that gradually progressed along the path during trials (see Figure 5.4). All participants completed these tasks once using their preferred (right) hand and once using their non-preferred (left) hand. This was counterbalanced so that every other participant began with their non-preferred hand. **Shape Accuracy (SA**) was recorded as a measure of tracing accuracy, as well as **Movement Time (MT)** to ensure compliance with the temporal constraints in the controlled speed conditions, and as a measure of movement speed in the preferred speed condition. The three tracing tasks were as follows:

(i) *Fast Speed Tracing (*23.64 mm/s)
(ii) *Slow Speed Tracing (*12.86mm/s)
(iii) *Preferred Speed Tracing (unconstrained)*

In all conditions the path remained static and was fully visible throughout the trial (NB. this was a slight variation on the task used in **Chapter 2**, where the path was only visible in between the two bars when speed was constrained – see **Section 2.2.2**). Each path thickness condition (i.e. narrow, medium and thick) was presented five times within each of the tasks (i.e. in the fast, slow and preferred speed versions) resulting in a total of 45 paths to trace, which were presented in a random order. The following instructions appeared on the screen at the start of the task; "*follow the path from start to finish as quickly as possible. You must NOT go outside of the path".*

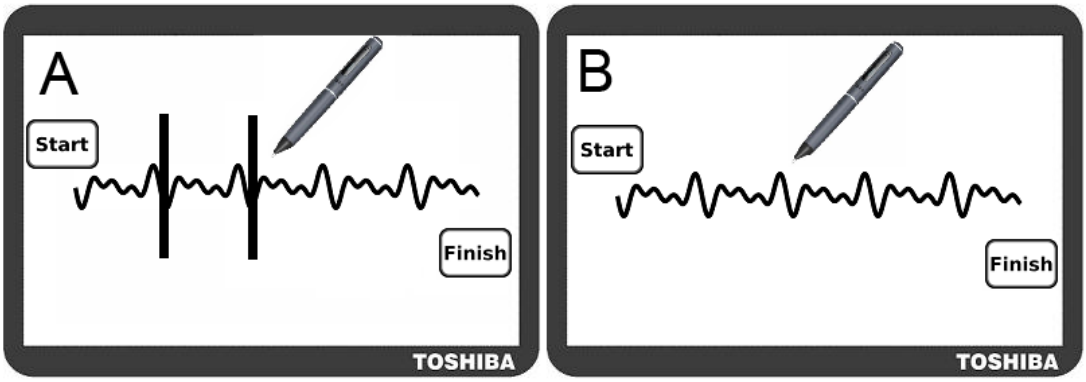

Figure 5.4 *Screen shots taken from the KineLab tracing tasks in Experiment Two (NB. not to scale).* ***(A)*** *Example of the constrained speed tasks (i.e. Fast and Slow Speed Tracing) in the narrow path thickness condition****. (B)*** *Example of the Preferred Speed Tracing task in the narrow path thickness condition.*

5.3.1.3 Analysis

Mean performance scores in the three path thickness conditions on each of the versions of the task were calculated (i.e. SA for Fast and Slow Speed Tracing; SA and MT for Preferred Speed Tracing), and separate mixed ANOVAs were applied, in order to examine differences between the task speed conditions, hands, and age groups. Extreme or missing data points were excluded from the analysis (e.g. some extreme values were caused by participants touching the screen with their hand), but there were no more than two values excluded for each outcome measure of each participant. Greenhouse-Geisser estimates of sphericity (ε) are reported where degrees of freedom have been adjusted.

5.3.2 Results

The results of data analyses for each of the tracing task conditions are provided in the following sections; Fast Speed Tracing (**5.3.2.1**), Slow Speed Tracing (**5.3.2.2**) and Preferred Speed Tracing (**5.3.2.3**).

5.3.2.1 Fast Speed Tracing

There was a main effect of hand on SA (F (1, 21) = 9.35, p < 0.05, η^2_p = .31) whereby tracing was more accurate when using the preferred hand. There was also a reliable main effect of path thickness on SA (F (2, 42) = 8.47, p < 0.05, η^2_p = .29, ε = .74) with thicker paths producing worse compliance with the shape. This is consistent with previous findings of increased corner-cutting with increased path thickness (**Chapters 2, 3** and **4**). While age group differences approached significance (F (1, 21) = 4.11, p = 0.056, η^2_p = .16) there were no reliable interactions, which suggests that manual asymmetries were equivalent across both groups of participants and in all path thickness conditions.

5.3.2.2 Slow Speed Tracing

Patterns of SA were similar to those during Fast Speed Tracing, but with no reliable differences between the age groups. There were, however, significant effects of hand (F (1, 20) = 8.13, p < 0.05, η^2_p = .29) and path thickness (F (2, 40) = 83.08, p < 0.001, η^2_p = .81) whereby tracing performance was better when the path was narrow and when the preferred hand was used. The lack of interactions once again demonstrates that manual asymmetries were equivalent across both age groups and all path thickness conditions.

5.3.2.3 Preferred Speed Tracing

Unlike the previous two tasks, preferred speed tracing allowed participants to move at their own pace and hence employ speed-accuracy trade-offs (i.e. increase MT to improve SA). Consequently both SA and MT data were examined in turn. While increased path thickness impaired accuracy (i.e. increased SA; F (2, 40) = 196.04, p < 0.001, η^2_p =.91), there were no effects of age or hand, and no reliable interactions for the SA measure. Movement Times on the other hand were affected by both age and hand condition. Figure 5.5 displays mean MTs for the young and old when tracing with the preferred and non-preferred hands on the narrow, medium and thick paths

(NB. mean MTs across both age groups and hands on the Fast Speed Tracing and Slow Speed Tracing and tasks are plotted in red and blue, respectively). Tracing was found to be significantly faster on the thicker paths (F (2, 42) = 75.38, p < 0.001, η^2_p =.78, ε = .69) and a reliable interaction between hand and path thickness (F (2, 42) = 3.73, p < 0.05, η^2_p = .115), revealed consistently slower tracing when the non-preferred hand was used, especially when the path was narrow. Older adults took significantly longer to trace paths compared to the young, evident in a significant main effect of age on MT (F (1, 21) = 13.75, p < 0.05, η^2_p =.40), but an absence of any further interactions for the MT metric reinforces the suggestion that manual asymmetries in tracing speed were equivalent across both groups of participants in this version of the task.

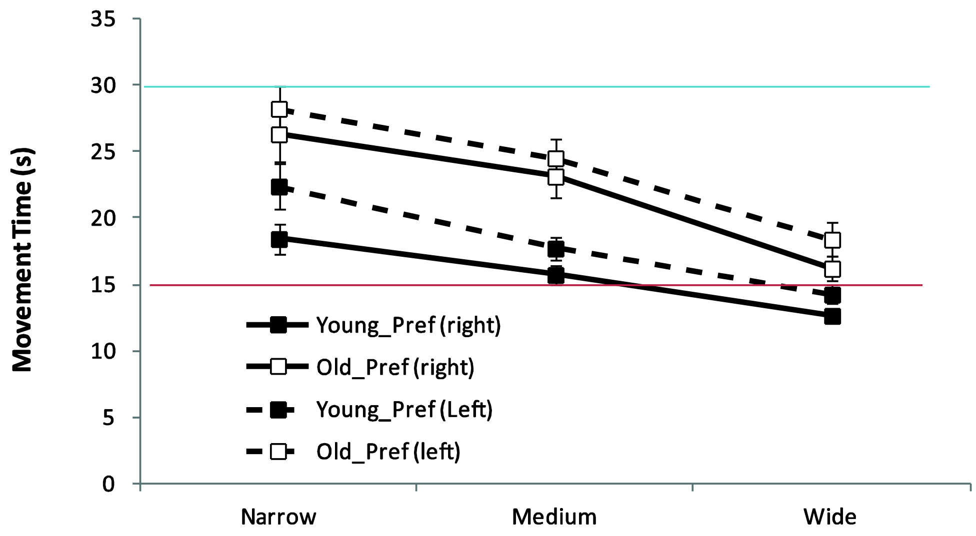

Figure 5.5 *Mean Movement Time (MT) in seconds (s) for the narrow (2mm), medium (4mm) and thick (6mm) paths for the preferred hand (solid line) and non-preferred hand (dashed line) in the Preferred Speed Tracing Task in Experiment Two. The coloured lines indicate mean MT in the Slow Speed Tracing (blue) and Fast Speed Tracing (red) versions of the task. Bars = Standard Error of the Mean.*

5.3.3 Discussion

The data from Experiment Two highlight an important issue when it comes to drawing conclusions about group differences based on performance of a task indexed by a single outcome measure. An obvious variable to use when examining tracing behaviour is accuracy (i.e. SA) as it indicates the extent to which participants maintain the shape of the path throughout the trial. While SA did reveal hand differences, there were no age group differences observed. In contrast, when tracing speed was unconstrained (i.e. Preferred Speed Tracing) a measure of MT provided an additional metric that was able to reveal both hand and age-group differences.

If SA had been the only measure used to address the question of whether manual asymmetries exist, different tasks would have led to opposing answers. There was evidence for manual asymmetries in SA on the Fast Speed and Slow Speed Tracing Tasks (as well as the Tracing component of the test battery in Experiment One), yet SA did not reveal asymmetries when participants paced themselves in the Preferred Speed version of the Tracing Task. The reason for this finding was made evident in the MT data – participants traded speed for accuracy and moved their non-preferred hand more slowly than their preferred hand, which allowed the two hands to perform at an equivalent level of accuracy. Difficulties in detecting group differences are also illustrated by the fact that the older participants slowed down their movements to a greater extent than the younger participants.

These results provide further evidence of participants strategically compensating for task demands. In all versions of the task, the thicker the path being traced the lower the SA. This finding confirms previous reports of participants making spatial and temporal adjustments to their movements in order to meet task demands (**Chapters 2, 3** and **4**). The fact that different age groups make different compensatory adjustments (**Chapters 2, 3** and **4;** Morgan et al., 1994: Welsh et al., 2007) means that it is not simple to compare performance between these groups, as well as confirming our suggestion that measurement difficulties can make it hard to detect subtle performance differences between the hands.

5.4 General Discussion

The experiments in **Chapter 5**, along with a number of previous studies, suggests that manual asymmetries may be absent or reduced in older adults (e.g. **Chapter 4**; Mattay et al., 2002; Ward & Frackowiak, 2003; Heuninckx et al., 2008; Przybyla et al., 2011; Wang et al., 2011). This behavioural observation has been connected with neurophysiological observations of reduced hemispheric asymmetries in older adults (Sailer et al., 2000; Calautti et al., 2001; Mattay et al., 2002; Ward & Frackowiak, 2003; Heuninckx et al., 2005; Naccarato, et al., 2006; Heuninckx et al., 2008). The present research aimed to test the hypothesis of reduced manual asymmetries resulting from reduced hemispheric asymmetries against an alternative suggestion – that manual asymmetries are subtle and highly dependent upon task demands, as well as the metric chosen to measure motor performance.

The experimental findings clearly differentiated between the alternative hypotheses as they: (i) provided evidence of manual asymmetries in older adults; (ii) established that different tasks yielded different patterns of asymmetries in both younger and older adults; and (iii) identified large individual differences in the measured manual asymmetries despite participants reporting similarly strong hand preferences. These observations all support the notion that differences between the hands are relatively small and thus highly sensitive to measurement. The present findings are not consistent with the hypothesis that motor output is affected by changes in hemispheric specialisation. Generalisation of the HAROLD hypothesis (Cabeza, 2002) to motor cortex and motor output implies that reduced manual asymmetries should be reliably observed in older people across a range of motor tasks. This study found that older people showed manual asymmetries in specific tasks whilst other tasks revealed no asymmetries in young or older adults.

This work therefore reconciles conflicting reports within the literature by demonstrating how empirical investigations of manual asymmetries are highly sensitive to task constraints (and individual differences within groups). There are a number of empirical studies that have reported reduced manual asymmetries in older populations (e.g. **Chapter 4;** Przybyla et al., 2011; Wang et al., 2011), and these have been used to support generalisation of the HAROLD model to motor cortex and movement control. Nevertheless, there are also cases where studies have found no evidence of age differences in manual asymmetries, (Mitrushina et al., 1995; Chua et al., 1995; Francis & Spirduso, 2000; Teixeria, 2008), or even identified an increase in asymmetries in older adults compared to the young (Goldstein & Shelly, 1981; Weller & Latimer-Sayer, 1985; Dolcos et al., 2002; Chua et al., 1995; Teixeria, 2008). It seems safe to conclude then, that the conflict between all of these studies simply relates to the precise constraints of the tasks used to explore the magnitude of differences in hand performance.

The fact that different tasks yield different asymmetries highlights two important issues with regards to the way in which manual asymmetries are examined. First, the process of capturing hand differences requires a task that yields optimal performance with both hands. Second, previous studies of age differences in manual asymmetries have often used combined speed-accuracy measures, or relied on speed as the only marker of performance (e.g. Francis & Spirduso, 2000; Chua et al., 1995; Weller & Latimer-Sayer, 1985; Goldstein & Shelly, 1981; Mitrushina et al., 1995; Mattay et al, 2002). This is problematic as spatial and temporal compensatory adjustments can then be missed. It is therefore essential not to base conclusions about group manual asymmetry differences on one outcome metric – one metric may miss effects that are manifest in other (unmeasured) aspects of performance.

The problem of missing effects in unmeasured aspects of performance is particularly germane when studying movement in older people. The tasks that were used in Experiment Two varied in temporal and spatial constraints. In the Slow and Fast Speed Tracing tasks the aim was to maintain spatial accuracy while speed was controlled. Shape Accuracy (SA) was hence selected as the marker of performance because it captured the extent to which participants maintained the shape of the path as they traced. Subsequent analyses revealed that participants were more accurate when tracing with the preferred hand, however there was no difference in accuracy between the young and old. A lack of age group differences would seem to contradict the age differences observed in Experiment One. As soon as participants were free to move at their preferred speed, however, age differences were revealed. Interestingly the age differences were only evident in the Movement Time (MT) metric (i.e. not in SA). Older participants preferred to trace at a slower pace, especially when using their non-preferred hand. This suggests that the old were able to match the accuracy of the young by slowing movements down. Experiment Two also confirms the previous findings of participants making strategic spatial adjustments to their movements in order to account for task demands (see **Chapters 2, 3** and **4**). The main effects of path thickness identified for tracing speed and accuracy showed that participants were more likely to reduce their speed, and subsequently achieve greater accuracy, when spatial demands increased (i.e. on the narrow paths).

The argument that manual asymmetries are subtle and difficult to measure should not be taken as an argument that manual asymmetries do not exist. The Edinburgh Handedness Inventory (EHI) clearly indicated a strong hand preference across the vast majority of our participants. Moreover, the participants frequently reported how much more difficult they found the task when using their non-preferred hand. Nevertheless, all participants were capable of completing the tasks with their non-preferred hand despite limited experience of holding a stylus (e.g. pen) with this hand. The theory of structural learning predicts the high level of performance that was identified in the non-preferred hand. The theory suggests that the control dynamics of holding a stylus and generating the appropriate forces are learned at an abstract ‘effector-independent level’. These control dynamics can then be exploited when generalising the skill – in this case to the non-preferred hand. The dynamics of controlling a stylus in the non-preferred hand will not be identical to those involved in the preferred hand but there will clearly be large similarities. The ability to generalise control dynamics would not allow the highest level of performance to be achieved (it seems logical to assume that would require direct trial-and-error learning of the precise dynamics), but would ensure a reasonable level of performance. It follows that learning a task with one hand will automatically allow some transfer to the other hand and thus necessitate sensitive measures to detect performance differences, as indicated by the current investigations.

In conclusion, the experiments in this chapter set out to explore whether reduced hemispheric specialisation could account for reports of decreased manual asymmetries in older adults (e.g. **Chapter 4**; Mattay et al., 2002; Ward & Frackowiak, 2003; Przybyla et al., 2011; Heuninckx et al., 2008; Wang et al., 2011). The subsequent pattern of results was not consistent with this view. Instead, the findings support an alternative hypothesis – that manual asymmetries are subtle, and their measurement in older groups is subject to two measurement issues; (i) a task must be sensitive enough to capture subtle differences in skill between the hands, and (ii) the metrics chosen to capture motor performance should be suited to the task demands and be cognisant of age differences in speed-accuracy trade-offs. The present findings demonstrate unequivocally that manual asymmetries in old and young adults alike are highly sensitive to task design and measurement.

Chapter 6

Age Differences in Motor Performance and Learning

6.1 Introduction

The research in this thesis so far has focused on age differences in motor performance. What can be concluded from this work is that movements become slower and less accurate with increasing age, and that older people are capable of adjusting the spatial and temporal dynamics of their behaviour in order to account for motor decline. Nevertheless, a further aim of the present PhD was to explore movement rehabilitation, and in order to do that, it is important to understand how people acquire new movement skills. In the context of stroke for example, individuals may need to re-learn how to move the affected limb and/or adopt new compensatory movements with the unaffected limb. An understanding of how motor learning is affected in a population that typically shows motor decline, such as older adults, therefore has clear clinical relevance. The experimental work of this chapter accordingly specifically examines the effects of ageing on motor sequence learning.

Humans learn to produce complex movement patterns throughout the lifespan. The impressive repertoire of skills possessed by human adults is a testament to the extraordinary neurophysiological architecture that underpins the motor system. However, the sheer number and diversity of skills seen in humans goes beyond those observed in any other animal species, and reflects the unique cognitive capabilities of Homo Sapiens. It is both useful and appropriate to consider the motor and cognitive systems of an individual human as being somewhat separate (e.g. Van Swieten, Van Bergen & Williams et al., 2010). The reality is, however, that the acquisition and production of complex movements rests upon the motor *and* cognitive apparatus working together in unison. In order to obtain a better understanding of skilled movement in humans, it is vital therefore to consider both the motor and cognitive systems and how these systems interact. This is of particular importance with regards to individuals who show deficits in skilled movement, as a greater understanding of the interaction between motor and cognitive processes would potentially allow for the development of tailored treatment regimes within a rehabilitation context.

Before considering in more detail how old age might affect the motor and cognitive aspects of sequence learning, it is important to reinforce, for clarity, the difference between the concepts of motor 'performance' and 'learning'. As stated in **Chapter 1** (**Section 1.1**), this thesis uses Schmidt and Vrisberg's (2008, p.11) definitions of these terms, where **motor performance** is defined as *'the observable production of voluntary action or a motor skill'*, which can be influenced by temporary factors such as mood or fatigue; and **motor learning** as *'changes, associated with practice or experience, in internal processes that determine a person's capability for producing a motor skill'*, which is assessed by observing its effects on measures of motor performance (e.g. a comparison of how speed or accuracy changes over time; Tresilian, 2012).

Past research, and the experimental findings in previous chapters of the present thesis have consistently demonstrated an age-related decline in motor performance, whereby older adults exhibit a reduction in speed and accuracy across a range of movement tasks (e.g. **Chapters 2, 3, 4** and **5**; Cooke et al., 1989; Desrosiers et al., 1995; Pohl et al., 1996; Contreras-Vidal et al., 1998). This can be explained by age-related physiological factors such as limited joint flexibility and muscle strength in the limbs (e.g. Barnett & Cobbold, 1968; Delbono, 2003), neural changes (e.g. Clark & Taylor, 2011; Mattay et al., 2002; Talelli, Ewas & Waddingham et al., 2008; Ward & Frackowiak, 2003), increased susceptibility to diseases that affect movement (e.g. stroke, arthritis) and compensatory changes in motor strategy (e.g. **Chapters 2** and **3**; Morgan et al., 1994).

Ageing is also associated with reduced ability to learn new movement skills. Voelcker-Rehage's systematic review of fine motor learning studies showed that older adults tend to learn at a slower rate and with poorer outcomes, for example in tasks involving aiming, fingertip force production and bimanual coordination (Swanson & Lee, 1992; Harrington & Haaland, 1992; Pratt, et al., 1994; Liao et al., 1997; Swinnen et al., 1998; Ketcham et al., 2002; Wishart et al., 2002; Voelcker-Rehage & Alberts, 2005; Shea et al., 2006; Boyd et al., 2008). These deficits in learning might, however, be restricted to more complex movement sequences, which would explain why some studies have failed to find age differences (Howard & Howard, 1989; Howard & Howard, 1992; Carnahan et al., 1996; Van Dijk et al., 2007) and, furthermore, suggests that the effects of ageing on motor learning may be task-specific rather than generalised (e.g. Seidler, 2006).

Given the decline in cognitive function that is also associated with old age (e.g. cognitive slowing, poorer working memory and reduced attention; Light & Anderson, 1985; Verhaeghen & Salthouse, 1997), one explanation as to why older adults have difficulties with the learning of novel complex movement patterns (e.g. Harrington & Haaland, 1992; Boyd et al., 2008), could be related to cognitive demand. When learning a novel series of movements, the sequence may require storage and/or attentional control resources based within working memory during the formation of a new long-term representation (Baddeley, 2012; Grafton et al., 1995; Sakai et al., 1998; Unsworth & Engle, 2005). Moreover, the cognitive literature suggests that there are age differences in *how* new movement sequences are acquired. One specific difference is in the way in which sequence information is encoded. Studies show that young people store parts of a motor sequence in 'chunks', which are internal representations of groups of elements that feature in a given sequence. Encoding sequences in this way saves limited processing resources – instead of recalling each move of a sequence individually, integrated sections of the array (typically three-to-five elements) can be combined and recalled together (Bo et al., 2009; Sakai, Kitaguchi et al., 2003; Verwey, 1996; Verwey, 1999; Verwey, & Eikelboom, 2003; Verwey et al., 2009; Verwey, 2010). In contrast, older adults do not always benefit from this encoding strategy and show minimal chunking compared to the young, and even when chunking is used, the chunks are comprised of fewer elements (Shea et al., 2006; Verwey, 2010). This is further supported by research on both immediate serial recall (Naveh-Benjamin, Cowan, Kilb, & Chen, 2007), and particularly long-term association formation (e.g. Howard, et al., 1991; Chalfonte & Johnson, 1996; Naveh-Benjamin, 2000; Castel & Craik, 2003), and strongly suggests that older adults have generalised difficulties in forming chunks in memory.

The fact that visuospatial working memory capacity predicts both movement chunk length and sequence learning in younger people (Bo & Seidler, 2009) implies that age-related cognitive decline in working memory processes (e.g. Salthouse, 1992; Reuter-Lorenz et al., 2000; Bo et al., 2009; Brown & Brockmole, 2010; Schneider-Garces et al., 2010) might underlie poorer sequence learning rates in older adults (e.g. Humes & Floyd, 2005). Bo et al., (2009), for example, found that older adults had both reduced visual working memory capacity, and produced shorter chunk lengths in a movement sequence learning task. Positive correlations between working memory and chunk length, and between chunk length and sequence learning were also observed (NB. no direct association between working memory and learning rate was found in this study). This could indicate that the parallel between the maximal ‘chunk’ size in sequence learning (e.g. three-to-five elements; Verwey, 1996) and the capacity of working memory (e.g. 4 chunks; Cowan, 2001) reflects a deeper relationship, which is consistent with convergent evidence showing that there is an important role for working memory in physically implementing short sequences of instructions (Gathercole, Durling & Evans et al., 2008).

The presence of cognitive decline in older groups certainly provides one explanation for the problems encountered by older people when faced with the task of learning a new movement skill. But what about the role of motor decline? Age differences in motor performance are indeed well-documented (as outlined previously), yet little is known about how this decline in underlying motor performance can impact upon novel motor learning. Motor learning undoubtedly relies on the higher-order processes of the cognitive system (i.e. the reasoning and memory processes that allow a new skill to be retained and retrieved; Rhodes, et al., 2004; Voelcker-Rehage et al., 2010), however the motor processes that underlie a particular movement skill are also essential – for example the functions of the motor system that allow one to physically move and coordinate one's fingers to type out a memorised password.

The two experiments that feature in the present chapter aimed to explore the relationship between motor performance and complex motor sequence learning: a series of movements that need to be performed in a particular order to produce a given outcome (i.e. the task goal). In classic motor learning theory, a central component of learning a complex movement pattern is the 'associative phase', which involves linking all of the 'component parts' into one smooth action (Fitts & Posner, 1967). Prior to the associative phase is the 'cognitive phase', which entails formulating a mental picture of a given skill (Fitts & Posner, 1967). While the modelling of motor learning has been refined greatly over the last four decades, most motor theorists accept the basic insights of Fitts and Posner's (1967) work regarding the key stages involved in movement learning. Thus, learning a complex movement pattern requires an individual to remember a series of movements (i.e. lower-order components) in order that these components can be linked into a smooth action, and ultimately become an automated, single, higher-order behaviour (Tresilian, 2012). Note too that there can be difficulties in defining the lower-order components in many complex movements, but this is an issue outside the scope of the current thesis.

It seems likely that individuals who moved more slowly because of motor decline would also experience an impact on their ability to learn a complex movement sequence. This hypothesis was based on the observation that movements consist of changes in body position over time. For example, the kinematics of pressing a light switch are provided by a depiction of how fingertip position unfolds over time – time is absolutely integral to the description of a movement. Accordingly, learning how to produce a novel movement sequence requires the system to have evolved such that information is stored regarding the relative timing of the lower-order components that comprise the entire movement sequence. It is reasonable to assume that there are costs associated with storing such information. It is well established that working memory has limited capacity; hence it follows that increasing the duration of the lower-order motor components might well decrease the number of components that can be held in working memory. Musical notation provides a useful analogy – bars can only contain a set number of beats so fewer notes can appear within a bar if the duration of the notes is longer. The number of beats within a bar is set by the time signature (i.e. working memory capacity in this analogy), but note duration is also a limit on the number of notes that can be held within a bar. This hypothesis suggests that poor movement learning in older people might be partly caused by an age-related decline in basic motor performance.

To test this hypothesis empirically, the effects of age and motor performance on movement sequence learning in healthy adults, was examined across two experiments. The aim of the first experiment was to develop a novel aiming movement sequence learning task, suitable for both younger and older adult participants, which would characterise the relationship between motor performance and learning. The task consisted of ‘training’ trials that prompted participants to move a mouse cursor to one of eight targets on a screen (i.e. a sequence of aiming movements). Following each training trial the participants were then required to recall the movement sequence without prompts. The second experiment employed this learning task in a new set of young and old participants, with participants using both the preferred (right) and non-preferred (left) hands. Because motor performance is impaired when using the non-preferred hand, it was expected that aiming movements would be slower than when using the preferred hand. This experiment provided a powerful test of the hypothesis – that longer duration movements would negatively impact on learning a complex movement sequence. Essentially, comparisons of sequence learning by hand and age group should allow the proportion of decline associated purely with motor differences to be calculated.

6.2 Experiment One

The experimental work of previous chapters shows that movement duration is increased in older adults. For example, older participants made slower aiming movements in **Chapter 5** (see **Section 5.2.2.2**), when no learning was required. The increased movement duration observed in the older age group yields the prediction that learning a sequence of aiming movements might be more problematic for older adults because of the temporal limits of working memory – regardless of whether there are also age-related deficits in cognition. The first experiment therefore used a task that required participants to *learn* a sequence of aiming movements in order to establish: (i) that the task could be completed by younger and older participants; (ii) ensure that the often reported age differences present in complex movement learning would be observed when using this task. The methodology (**Section 6.2.1**), results (**Section 6.2.2**) and a brief discussion (**Section 6.2.3**) for Experiment One, are provided in the next sections.

6.2.1 Method

Participant details are given in **Section 6.2.1.1**, followed by a detailed description of the motor learning task in **Section 6.2.1.2**. Outcome metrics for the measurement of motor performance and learning, and the chosen method for data analysis, are detailed in **Section 6.2.1.3**.

6.2.1.1 Participants

Twenty healthy individuals with no previous history of ophthalmological or neurological problems formed an opportunistic sample (NB. participants were staff and students at University of Leeds and members of South Parade Baptist Church and Teesside Musical Theatre Company). All participants were right-handed as indexed by the EHI, with a mean score of

96.5 (*SD* = 9.88) out of the maximum 100. Participants were split into two age groups. The ‘young’ group (6 females, 4 males) were aged between 18 and 40 years (mean age = 24.9, *SD* = 7.45) and the ‘old’ group (6 females, 4 males) were aged between 60 to 75 years (mean age = 69.60, *SD* = 4.12). All participants gave their written informed consent, and the experiment complied with ethical guidelines approved by the University of Leeds ethical committee, in accordance with the Declaration of Helsinki.

6.2.1.2 Procedure and Apparatus

A motor sequence learning task was created using KineLab (Culmer et al., 2009). Participants used a tablet PC (same as used previously, see **Section 2.2.2**) and standard computer mouse to learn a sequence of movements made to eight target locations on the screen (see Figure 6.1c). The task consisted of a series of ‘training’ and ‘test’ trials which alternated to allow 14 opportunities each for participants to practice and then reproduce the sequence (i.e. training trial followed by a test trial x 14 repetitions = 28 trials in total). Figure 6.1a shows the screen as it appeared to participants in the training trial, where there was one central white box (height = 25mm; width = 25mm), encircled by eight identical ‘target location’ boxes (height = 25mm; width = 25mm). In the training trials, an arrow appeared in the central box as a cue for participants to move the circular cursor to the target location adjacent to the direction of the arrowhead (e.g. the correct response would be to move the dot to the top left box for the example given in Figure 6.1a). After each individual move to a target location, participants returned to the centre, where the next arrow in the sequence would appear (NB. no mouse clicks were required). There were a total of 30 moves to learn, which followed an irregular pattern (see example traces from a participant completing the training trial in Figure 6.1b). After each training trial, participants were required to attempt to reproduce the sequence of moves they had just been making, by moving the cursor back-and-forth between the central box and target locations as quickly and as accurately as possible. Examples of a training and test trial are shown in Figures 6.1d and 6.1e respectively. To ensure participants’ complete understanding of the task, standardised instructions were presented in a series of slides, which included screen shots of the two trial types (similar to those pictured in Figures 6.1a-b). Participants were also given two practices each of a training and test trial which featured a 16-move sequence different to that used in the experimental task.

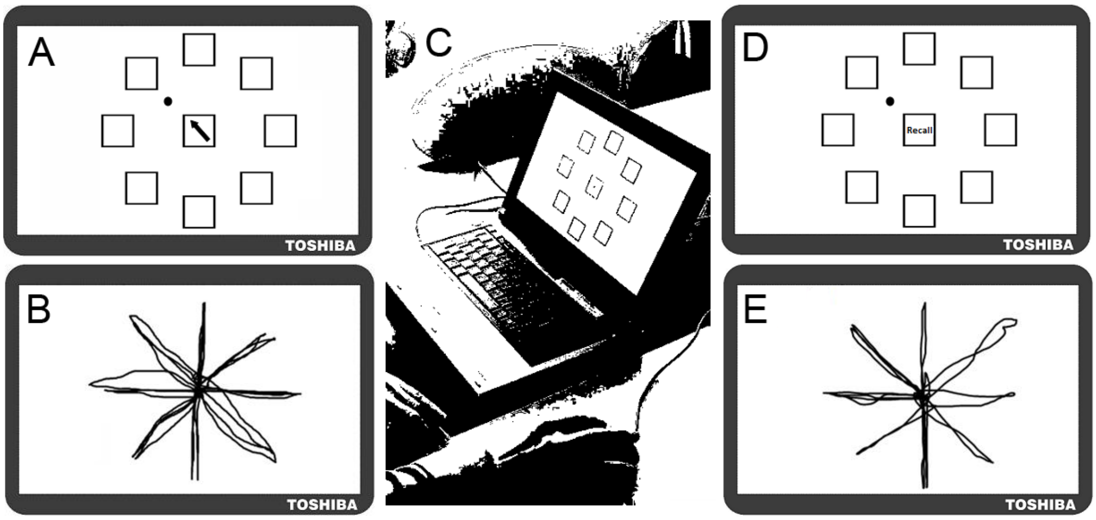

Figure 6.1 *Screen shots of the learning task as it appeared to participants in Experiments Two and Three (NB. not to scale).* ***(A)*** *Training trial whereby participants moved the dot into the box corresponding to the direction indicated by an arrow in the central box (e.g. top left in the example pictured).* ***(B)*** *Test trial in which participants recalled the pattern of movements previously displayed in the training trial.* ***(C)*** *Older adult completing the learning task using a standard computer mouse. Example traces of one participant's movements during* ***(D)*** *a training trial and* ***(E)*** *a test trial.*

6.2.1.3 Analysis

The following outcome measures were calculated to identify speed and accuracy of recall (i.e. motor learning) in the test trials, and level of motor performance in the training trials.

(i) *Test trial measures:* Number of moves recalled in the correct sequential order **(Correctly Recalled; CR)**, with a maximum score of

30. Points were not gained for incorrect moves, but no points deducted. In order to score a point, a participants' move to target had to match that targets' position in the 30-move sequence, which meant that a participant could continue to score points after producing any incorrect move(s) if they were able to pick up the sequence from the point of their error (e.g. a participant might get the first five moves right, the 6th move wrong, and then continue the sequence at with the correct target for move 7 and continue to score points thereon). Furthermore, in cases where the participant went 'adrift' by one move at some stage in the sequence (e.g. recalled one incorrect move but then continued with what would have been the correct move had they not incurred the error), the error was not counted and participants would continue to score as normal. **Recall Movement Time (MT_r)**, which was the mean time (s) taken to move the mouse from the centre to a target box when recalling the sequence (i.e. a measure of recall speed). Because different numbers of moves could be recalled, the MT was calculated per item.

(ii) *Training trial measures:* **Path Length (PL)** indicated the length of the path (mm) taken by participants throughout an entire training trial, thus providing a marker of movement accuracy (i.e. straight paths will be shorter)*;* **Training Movement Time (MT_t)**, which was the time (s) taken to complete a training trial from start to finish.

For the analysis of data from the test trials, mean values for CR and MT_r across the first five trials (F5) and last five trials (L5) were calculated. These data were input into two separate mixed-model ANOVAs in order to compare speed and accuracy of sequence recall between the beginning and end trial blocks (i.e. to identify progression of learning from the first to second half of the task), and between the old and young age groups. For the training trials, mean values for PL and MT_t across the L5 trials were used as a baseline measure of motoric performance.

6.2.2 Results

The results of data analyses for the test and training trials are given in **Section 6.2.2.1** and **6.2.2.2**, respectively.

6.2.2.1 Test Trials

The ANOVA for number of moves recalled in the correct sequential order (CR) revealed a significant effect of age (F (1, 18) = 16.02, p < 0.01, η^2_p = .47), whereby the young learned a greater number of moves than the old (see Figure 6.2a). A main effect of trial block (F (1, 18) = 36.85, p < 0.001, η^2_p = .67) also shows that all participants had learned a significantly greater number of moves by the end of the task (mean CR for L5 = 14 items or 45% of the sequence) compared to the first half (mean CR for F5 = 8 items or 27% of the sequence). The interaction between age and trial block was only marginal (F (1, 18) = 4.16, p = 0.056, η^2_p = .19), but would suggest that the young group had learned disproportionally more than the older group by the end of all the training.

Speed of recall was also measured during the task, hence Figure 6.2b shows the mean Recall Movement Time (MT_r) for old and young participants on the F5 and L5 blocks of the test trials. Analyses of the MT_r data showed that participants were quicker to recall moves in the L5 trials compared to the F5 (F (1, 18) = 11.25, p < 0.05, η^2_p = .39), and the young also recalled moves significantly faster than the old (F (1, 18) = 12.24, p < 0.05, η^2_p = .41). There was no age × trial block interaction (F (1, 18) = .43, p > 0.05).

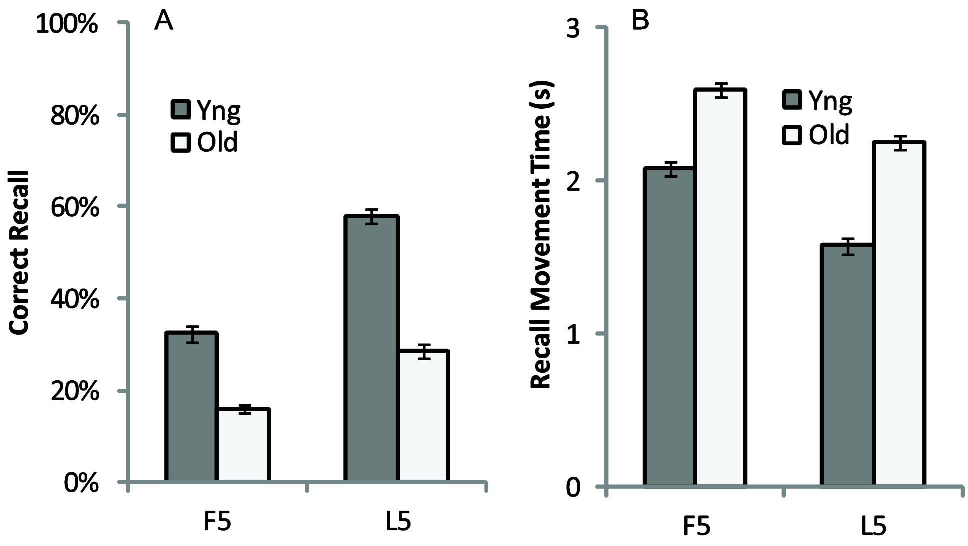

Figure 6.2 *Measurements of recall and movement time recorded in the test trials of Experiment One for young (dark grey bars) and old (light grey bars) groups, averaged across the first five trials (F5) and last five trials (L5).* ***(A)*** *Proportion (%) of movements recalled in the correct sequential order at test (CR). This provides a measure of sequence learning.* ***(B)*** *Mean time taken between moves during free recall (MT_r). A change in MT_r indicates improvements in performance (e.g. reduced MT_r suggests learning). Bars = Standard Error of the Mean.*

6.2.2.2 Training Trials

The young demonstrated superior motor performance in the training trials, whereby t-tests revealed that Training Movement Time (MT_t) was significantly shorter in the younger group (t (18) = 2.54, p < 0.05). There was, however, no age difference in accuracy of aiming movements, as indicated by PL (t (18) = 1.25, p > 0.05), presumably because the old moved at a slower pace, thus allowing them to maintain comparable accuracy to the young (i.e. because of speed-accuracy tradeoffs).

6.2.3 Discussion

The results of Experiment One show that the task provided a useful measure of movement sequence learning in younger and older adults. All of the participants showed evidence of learning the movement sequence over the set of training trials. The task was neither too difficult (i.e. too little learning), nor too easy (i.e. the sequence learned too quickly), hence it provides a useful metric of learning ability. The experiment also reinforces previous reports of reduced motor learning found in older adults (see Voelcker-Rehage, 2008, for a review). There are a number of possible reasons why the older adults might have shown reduced ability to learn the sequence. One highly plausible reason is that older adults have poorer cognitive capabilities. More interestingly, there might also be a relationship between the reduced motor performance of older participants (as indexed by increased movement duration found in Experiments One and also in previous chapters, for example **Chapter 5**) and their reduced motor learning ability (as shown in Experiment One). Between-group studies cannot address this question satisfactorily because it is difficult to disentangle the influence of cognitive differences on learning rates. The second experiment of the present chapter therefore studied young and old participants' learning of sequences with both their preferred and non-preferred hands, in order to vary motor performance within individuals, and examine whether sequence learning would be affected.

6.3 Experiment Two

The findings of Experiment One are consistent with the hypothesis that there might be a relationship between motoric performance level and sequence learning, as older participants were found not only to recall fewer moves (than the young) at test, but also showed increased movement duration during the training trials. There are two possible explanations for this: (i) that encoding a movement sequence into memory has an influence over the speed of movement (i.e. learning alters motor performance, in this case movement duration), or (ii) that less skilled movements have a causal role in impairing motor sequence learning (i.e. movement performance level affects learning). To distinguish between these explanations a second experiment was conducted on a new set of old and young participants, this time measuring learning in both the preferred and non-preferred hands. The first explanation would predict impaired recall in the old compared to young, but no differences between which hand was used to perform the task. The second explanation would predict impaired recall in the old, but also for both age-groups when using the non-preferred hand (i.e. superior motor performance is expected in the preferred hand for this type of task, as found in **Chapter 5**, **Section 5.2.2.2**). The same motor learning task paradigm was used as in Experiment One, but because both hands were being tested, the number of movements to be learnt was halved in order to keep overall experiment testing time equivalent, and to avoid participant fatigue. Methodology, results and a brief discussion for Experiment Two are given in **Sections 6.3.1**, **6.3.2** and **6.3.3**, respectively.

6.3.1 Method

Section 6.3.1.1 provides details of the new set of participants recruited for Experiment Two. The modified version of the motor sequence learning task is described in **Section 6.3.1.2**, along with methods of data analysis in **Section 6.3.1.3**.

6.3.1.1 Participants

Thirty seven right-handed healthy individuals with no history of ophthalmological or neurological problems were selected from an opportunistic sample (mean EHI score = 87.40, *SD* = 15.20). Eighteen participants (11 female, 7 males) aged between 20 and 25 years (mean age = 20.83, *SD* = 1.12) formed the 'young group'. Nineteen participants (14 female, 5 males) aged between 61 and 80 years (mean age = 70.79, *SD* = 6.09) were in the 'old group'. Young participants were recruited from the University of Leeds and older adults were from local community centres in London and Leeds. The Addenbrooke's Cognitive Examination Revised (ACE-R) (Mioshi et al., 2006) was administered to older participants as a measure of basic cognitive ability and the mean score indicated no cognitive deficit at 91.53 out of 100 (*SD* = 5.54). The University of Leeds ethics and research committee approved this study and all participants gave written, informed consent in accordance with the Declaration of Helsinki

6.3.1.2 Procedure and Apparatus

KineLab (Culmer et al., 2009) was used to create two new versions of the motor sequence learning task used in Experiment One, each with a different 16-move sequence. Participants completed ‘version one’ of the task using their preferred hand and ‘version two’ with their non-preferred hand. The order of which hand/version was administered first was counterbalanced across participants. Instructions were the same as for Experiment One and participants were given two opportunities to practice the training and test trials, (NB. this included a different 16-move sequence to those used in the experimental tasks). Each task had 10 training and test trials, resulting in a total of 20 trials per task.

6.3.1.3 Analysis

Outcome measures were identical to those used in Experiment One (CR, MT_r, PL and MT_t). For the test trial analysis, mean scores across the L5 trials were calculated and two separate mixed-model ANOVAs applied in order to examine age and hand differences in motor learning (CR and MT_r). Two further ANOVAs were carried out in order to identify the effects of hand and age on motor performance during training (PL and MT_t) – this time training data was averaged across all 10 trials because there was no apparent change in performance throughout the task.

6.3.2 Results

The results of data analyses for the test and training trials are given in **Section 6.3.2.1** and **6.3.2.2**, respectively. A more detailed look at the chunking strategies applied by participants in this experiment is provided in **Section 6.3.2.3**.

6.3.2.1 Test Trials

It was previously found in Experiment One that participants became quicker and more accurate at recalling moves at test as the trials progressed. In the present experiment, a similar increase in speed and accuracy of recall is apparent (see Figures 6.3a-b) but particularly for the young, and in the preferred hand condition. To formally analyse these differences, data from the L5 trials was examined (i.e. the average across the last five trials; see Figure 6.4). The ANOVA for CR identified a main effect of age group (F (1, 35) = 135.5, $p < 0.001$, $\eta^2_p = .79$), a main effect of hand (F (1, 35) = 9.13, $p < 0.01$, $\eta^2_p = .21$) and a hand × age group interaction (F (1, 35) = 4.73, $p < 0.05$, $\eta^2_p = .12$). This indicates that the young recalled a greater number of moves in the correct sequential order than the old, the preferred hand more than the non-preferred hand, and the hand difference was greatest for the young (see Figure 6.4a). The ANOVA for MT_r also revealed a significant main effect of age group (F (1, 35) = 34.74, $p < 0.001$, $\eta^2_p = .50$) and hand (F (1, 35) = 37.73, $p < 0.001$, $\eta^2_p = .42$) but there was no interaction (F (1, 35) = .17, $p > 0.05$). Hence younger participants were faster in recalling movements at test, and the preferred hand was quicker than the non-preferred hand (see Figure 6.4b).

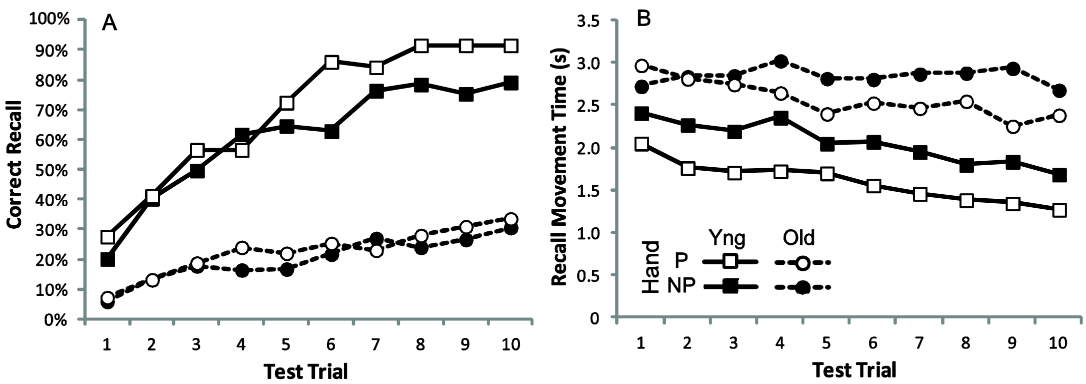

Figure 6.3 *Measurements of recall and movement time recorded in Experiment Two for the preferred (right) hand (empty symbols) and non-preferred (left) hand (filled symbols) in the old (dashed line and circles) and young (solid line and squares) groups for each of the 10 test trials.* ***(A)*** *Mean*

number of moves recalled in the correct sequential order (CR). ***(B)*** *Mean time taken between moves during free recall (MT_r).*

6.3.2.2 Training Trials

Analyses of data from the test trials showed that time taken to recall the motor sequence, and the number of moves recalled in the correct order, was reduced in the older group and when participants used the non-preferred hand. In order to identify the role of motor performance in impaired recall accuracy and speed at test (i.e. CR and MT_r), ANOVAs were applied to the PL and MT_t data recorded during training.

The PL analysis found main effects of age group (F (1, 35) = 19.42, p < 0.001, η^2_p = .36) and hand condition (F (1, 35) = 12.25, p < 0.001, η^2_p = .26) as well as an age × hand interaction (F (1, 35) = 6.51, p < 0.05, η^2_p = .16), hence the PL difference between the hands was more exaggerated in the older group (see Figure 6.4c). Similarly, the ANOVA for MT_t also revealed effects of age group (F (1, 35) = 20.12, p < 0.001, η^2_p = .37) and hand (F (1, 35) = 51.04, p < 0.001, η^2_p = .59) and a significant hand × age interaction (F (1, 35) = 7.98, p < 0.05, η^2_p = .19) which confirmed increased manual asymmetries in the older group (i.e. a greater difference in movement duration between the preferred and non-preferred hand in the old; see Figure 6.4d).

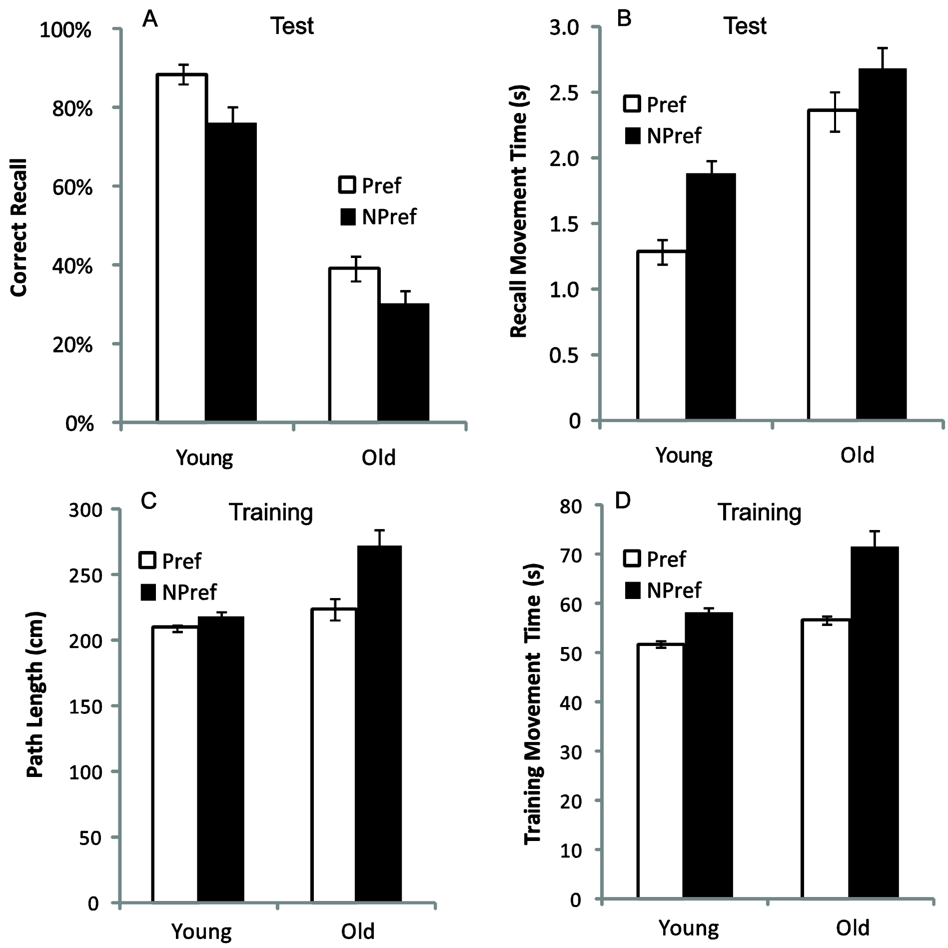

Figure 6.4 *Measurements of the preferred (right) hand (white bars) and non-preferred (left) hand (black bars) for old and young participants averaged across the last five (L5) test trials* ***(A,B)*** *and training trials* ***(C,D)*** *in Experiment Two.* ***(A)*** *Proportion (%) of movements recalled in the correct sequential order at test (CR)* ***(B)*** *Mean time taken between moves during free recall* (MT_r)*.* ***(C)*** *Length of entire path taken throughout a training trial (PL).* ***(D)*** *Time taken to complete a training trial from start to finish* (MT_t)*. Bars = Standard Error of the Mean.*

6.3.2.3 Chunk Length as a Function of Age and Hand

To determine whether there were age differences in the encoding strategies used by participants, the average change in the number of moves correctly recalled in sequence was calculated for each test trial (see Table 6.1). It can be seen that older adults did not usually encode chunks of multiple movements on each trial, and instead tended to increase the number of moves recalled by only one at a time. In contrast, the young seem to have stored the motor sequence in chunks of three or four, certainly over the first three trials (which captures the majority of the required moves). Interestingly the chunk size appears larger for the preferred hand in the younger group, suggesting that motor performance during training (i.e. when the preferred hand is used), could perhaps interact with strategic encoding.

Table 6.1 *The average number of additional items recalled in each test trial (i.e. over and above those recalled in the previous test trial) for old and young participants, when using the preferred (right) and non-preferred (left) hand to complete the motor sequence learning task in Experiment Two.*

		Test Trial									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Young	Left	3	3.5	2	2	2	0	1	0	0	0
	Right	4.5	3	3	0.5	1.5	2	0	0	0	0
Old	Left	0	1	1	0	1	0	1	0	0	1
	Right	1	1	1	1	0	0	0	1	1	1

6.3.3 Discussion

The second experiment confirmed the results of the first experiment, whereby older adults showed reduced learning relative to the young. It is clearly the case that there are often cognitive differences between younger and older adults (e.g. Light & Anderson, 1985; Verhaeghen & Salthouse, 1997), and these cognitive differences could indeed explain age differences in an individual's ability to learn a complex sequence of movements. However, it is possible that the reduced baseline level of motor performance typically observed in older adults (i.e. slower, less accurate movements) might also be a contributing factor. This hypothesis was tested in Experiment Two by asking participants to use both their preferred and non-preferred hand to complete the sequence learning task. The underlying cognitive capabilities of an individual remain constant regardless of which hand is used to undertake the task; hence differences in learning between the hands would support the hypothesis, that reduced motor performance affects motor learning. As expected, the data showed unambiguously that both younger and older participants learned more of the sequence, and recalled it at a faster pace, when using their preferred hand. These results support the idea that reduced motor performance will impact on complex movement sequence learning in addition to any difficulties caused by cognitive decline.

It is also notable that age and handedness significantly interacted in different directions for the training and test trials. At test, handedness had a larger impact on the young group, which according to Figure 6.4, emerged during the latter half of the trials. As the younger adults were producing many more movements in the later trials, the effect might therefore have been cumulative; the more movements that had to be stored and subsequently implemented from memory using the non-preferred hand, the greater the impact of this relative motoric inefficiency. In contrast, as the older group were only able to produce slightly longer sequences with each new trial, there was less opportunity for handedness to impact on performance. When participants were trying to learn the sequence in the training trials, however, the cognitive effects of reduced working memory capacity and/or processing speed were compounded by reduced motor performance in the non-preferred hand, thus leading to larger effects of handedness in the older group during this phase.

6.4 General Discussion

It is well documented that the cognitive and motor processes involved in motor learning diminish with age (e.g. Light & Anderson, 1985; Verhaeghen & Salthouse, 1997). It was therefore predicted that older adults would show poorer motor sequence learning compared to the young. In line with previous observations of age-related declines across visuo-motor sequence learning tasks (e.g. Bo et al., 2009; Humes & Floyd, 2005; Turcotte, Poirier &

Gagnon, 2005), this hypothesis was supported by the findings of Experiments One and Two, which both identified significantly poorer recall in the old (i.e. they remembered fewer moves and recalled them at a slower pace).

The experimental work of this chapter also provides new insight into the relationship between motor performance and movement sequence learning. Older adults were previously found to show reduced motor performance during a simple aiming task – older adults took longer to move the pen between targets (see **Chapter 5**, **Section 5.2.2.2**). Experiment One in the present chapter likewise revealed reduced movement speed in the older group when making similar aiming movements during the training phase of the sequence learning task (i.e. reduced motor performance, as indicated by increased movement duration). The second study then tested the hypothesis of whether motor performance directly affected movement sequence learning, by having a different group of old and young participants perform the learning task with both their preferred and non-preferred hands. The results confirmed that the old learned less of the motor sequence than the young, but more critically, in both groups, use of the non-preferred hand caused reduced learning compared to when using the preferred hand. At recall fewer correct (and generally slower) movements were observed in the older group, and fewer correct (and generally slower) movements for the non-preferred hand in *both* age groups. This essentially suggests that motor sequence learning is influenced by underlying motor performance.

Overall the present findings support the conjecture that the motor and cognitive systems play essential, but independent, roles in movement sequence learning. This is consistent with Van Swieten et al.'s (2010) suggestion that the motor and cognitive systems are somewhat separate, yet interact in numerous everyday activities. This raises the question of whether the motor performance of participants in this chapter was influenced by the quality of the memory they formed for the movement sequence. While it is apparent that the acquisition of accurate memorial representations supported subsequent skilful execution of movement at test, it appears that in the context of the featured task, motor performance affected the learning of movements, rather than the reverse.

Clearly, motor performance does not explain all of the group differences that were observed in the experiments. For example, during the training phase, motor performance in the non-preferred hand of the young was similar to the preferred hand of the old, however there was a large difference in the number of correct movements recalled between these hands/groups (i.e. a difference of 45% correctly recalled). To further examine the group differences, chunk sizes used by the old and young when recalling the sequence were calculated and are displayed in Table 6.1. It can be seen that the young used a standard chunk size of 3-5 items (particularly when recalling the first 10 items), which is comparable to previous research (e.g. Bo et al., 2009). Such chunking during visuomotor sequence learning improves processing efficiency, and is thought to be critical in representing lengthy motor sequences (Sakai et al., 2003). In contrast, the old group did not seem to effectively add multi-movement chunks to their overall representation of the sequence on each trial, instead the number of items recalled tended to increase by a single item at a time. This pattern fits with previous research showing age-related impairments in chunking (e.g. Bo et al., 2009; Verwey, 2010) and association-formation (e.g. Naveh-Benjamin, 2000). Bo et al. (2009) recently observed impaired learning of motor sequences in older adults. Specifically, visuo-spatial working memory ability was found to indirectly predict learning in older adults, via a mediating effect on the size of chunks that could be constructed. It is therefore possible that age differences in learning of motor sequences are at least partly the result of reduced working memory capacity constraining the size of chunks that can be built on each trial, with older adults apparently limited to the acquisition of a series of single movements in the present study.

The ability for procedural memory to inform the necessary sequence of actions to achieve a goal is crucial for carrying out many activities of daily living (e.g. tying shoelaces), but it also underpins highly skilled (and risky) activities such as driving, or carrying out complex surgical procedures. Such highly practiced abilities, eventually stored as procedural knowledge, must initially be acquired through learning processes that are potentially more resource-intensive and controlled (e.g. Baddeley, 1986; Norman & Shallice, 1986), and require construction and temporary storage in working memory. It is this initial learning phase that was examined in the present experimental work. Temporary storage and control processes are likely to become less critical over time as learning proceeds, and procedural memory develops. In line with this, Sakai et al., (1998) suggested a shift in the importance of brain regions during the transition from declarative to procedural memory in visuo-motor sequence learning – early learning primarily activates frontal areas (particularly the DLPFC and pre-SMA), with a shift to parietal areas as sequences become consolidated. Observations of age and hand effects in Experiment Two of this chapter may therefore reflect the potential roles of the DLPFC and pre-SMA in initial visuo-motor learning.

While the present work examined some of the deficits associated with old age, the findings also have implications for other groups that experience motor deficits. One example is children with developmental coordination disorder (DCD), who make up approximately 5% of the population (Van Swieten et al., 2010). Children with DCD experience a host of related problems that often become particularly apparent in mainstream education. Slower movements could lead to greater demands on working memory within many school learning tasks. Working memory itself provides a good predictor of scholastic ability (e.g. Gathercole, Brown, & Pickering, 2003), but given the co-morbidity of DCD with other developmental problems, there could well be complex interactions between memory and motor deficits that results in poorer educational outcomes for these groups of children. In line with this, it has been found that children with poor working memory have problems in following and implementing instructions within the classroom (e.g. Gathercole, Lamont, & Alloway, 2006), thus it would be of value to establish how motor performance might also be involved in such tasks.

Interestingly the motor basis of complex movement tasks often makes it difficult to explicitly recall the necessary action sequence outside of the required context or without miming the action – for example recalling the digit sequence of your PIN number without the spatial layout of the keypad. The research in this chapter certainly suggests that there are important interactions between motor performance levels and motor sequence recall, which seems to be true of motor impairment caused by age-related decline, but also when using the non-preferred hand. A crucial aim for future research should be to determine how action and memory interact, in order to fully understand how skilled actions are performed and how they might be improved in cases of impairment. The next chapter accordingly examines the effects of tDCS on motor learning in healthy older adults.

Chapter 7
Can Transcranial Direct Current Stimulation (tDCS) Improve Motor Learning?

7.1 Introduction

Chapter 6 examined the effects of motor performance (e.g. speed and accuracy of movement) on motor learning, and considered age differences when healthy participants learned a complex sequence of aiming movements. The main reason for addressing motor learning as part of this doctoral work was to relate findings to movement rehabilitation, which aims to help individuals re-learn motor skills, or adopt new ways of moving after injury. Stroke is one such illness that is particularly common within the older population and can cause anything from mild to more severe motor problems (American Heart Association, 2008). In this context, physical therapies have been widely applied (see **Chapter 1**, **Section 1.3.1**); though more recently there has been great interest in the use of non-invasive brain stimulation (NIBS) techniques to 'accelerate' motor recovery after stroke. The present chapter will therefore focus on Transcranial Direct Current Stimulation (tDCS), a form of NIBS that has been found to improve motor outcomes in the past (e.g. Nitsche & Paulus, 2001). The experiments presented in this chapter aimed to develop a task, suitable for use with young and older adults alike, which could identify the effects of tDCS on motor learning. The tasks developed were also designed with the intention of providing an informative method of assessing motor recovery within a clinical context (e.g. post-stroke).

Section 7.1.1 provides a detailed description of the methodology and mechanisms underlying the effects of tDCS. **Sections 7.1.2 – 7.1.4** include a comprehensive literature review of past research findings regarding the effects of tDCS on upper-limb motor control (**7.1.2**) and learning (**7.1.3**) in healthy people, and in patient populations following stroke (**7.1.4**). Aims of the present research are outlined in **Section 7.1.5**.

7.1.1 Transcranial Direct Current Stimulation (tDCS): Methodology and Mechanisms

The concept of applying direct currents (DCs) to the nervous system dates back to animal research conducted in the 1960's and 70's, which found that DCs could alter the electrical response of neurons in cats, monkeys and rats (Fuortes, 1954; Hern et al.,1962; Bindman, 1962; Bindman et al., 1964). For example, Bindman (1962) found that stimulation-induced changes in the neuronal excitability of the rat cortex continued for up to three hours post-stimulation when the current was applied for 5min or more. Work by Fehlings and Tator (1992) later suggested that DC currents might also assist in the recovery of a damaged nervous system – in their case the injured spinal cord axons of the rat. Though interest in this technique initially waned back in the 70's, the potential for DC currents to modify the workings of the human nervous system is currently a 'hot topic' in contemporary science. The method is also gaining significant attention with regards to its potential therapeutic application.

In human research, DCs have been used to alter brain activity non-invasively through surface electrodes on the scalp, a method most commonly referred to as 'Transcranial Direct Current Stimulation (tDCS)'. Low amplitude direct currents are applied through saline-soaked electrodes that pass though the skull to stimulate the brain. The current is transmitted from a battery or mains powered constant stimulator, with 0-4 mA voltage capacity. The positive (anode) or negative (cathode) electrode is positioned over the area of interest (e.g. the primary motor cortex; M1) and a further electrode on a reference region to complete the circuit. A supraorbital region (which is the method used in this chapter), or area outside of the skull such as the chest, chin or collarbone is often chosen as a reference, in order to minimise stimulation effects on the underlying brain tissue. Once the current penetrates the brain, it alters cortical excitability by modifying neuronal potentials and firing rates in response to stimuli (Williams, Imamura & Fregni, 2009).

Priori, Beradelli and Rona et al., (1998) were the first to apply tDCS in this way to the human brain, specifically to the M1 region. The tDCS was administered and outcomes were examined by measuring motor evoked potentials (MEPs) initiated by Transcranial Magnetic Stimulation (TMS). Unlike tDCS, TMS is a NIBS technique that modifies neuronal activity through electromagnetic induction; an electrical current is sent through a wire coil held over the skull to create a magnetic field and the resultant magnetic pulse travels through the skull and into the brain tissue where a further electrical current is induced and alters neuronal excitability (e.g. Pascual-Leone, Valls-Sole, Wasserman & Hallett, 1994; Siebner, Lang & Rizzo et al., 2004). The method can be used to examine the effects of tDCS by generating an MEP with TMS after the tDCS intervention, then recording changes in MEPs through surface electrodes typically in a muscle of the contralateral hand. The ground-breaking work of Priori et al., (1998) subsequently found that anodal DCs (AS) alternated with cathodal DCs (CS) led to a suppression of activity in M1. Further studies then served to define the 'polarity-specific' effects of tDCS whereby AS has been consistently found to enhance cortical excitability, and CS decrease brain activity, with effects lasting for at least an hour post-stimulation (Nitsche & Paulus, 2000; Nitsche & Paulus, 2001; Nitsche et al., 2003a; Nitsche & Paulus, 2011; Jacobson et al., 2012).

The mechanism of action underlying the cortical effects of tDCS is thought to be related to the impact on neuron membrane potentials. Essentially tDCS acts as a 'neuro-modulator'; rather than forcing an action potential (i.e. which is what occurs with TMS, a 'neuro-stimulator') it changes the resting membrane threshold of neurons by altering the balance of ions inside versus outside of the neural membrane. Anodal tDCS increases the resting membrane potential and hence 'depolarises' neurons whereas CS 'hyperpolarises' membrane potentials (Nitsche et al., 2003). In other words, tDCS does not cause a resting neuron to fire, but instead modulates the membrane potential in a way that primes the brains response to any incoming inputs (e.g. when tDCS is coupled with a behavioural task). There is evidence to support this view based on functional Magnetic Resonance Imagining (fMRI) studies that have found that tDCS can modulate cortical activity initiated by simple hand movements (e.g. Jang, Ahn & Byun et al., 2009; Kwon & Jang, 2011; Venkatakrishnan & Sandrini, 2012; Stagg, O’Shea & Kincses et al., 2009).Neuroimaging research does suggest, however, that the modulating effects of tDCS are not focused on one isolated region of interest (i.e. directly beneath the electrode). Using Position Emission Tomography (PET), Lang, Siebner and Ward et al., (2005) found that AS and CS of the left M1 altered regional cerebral blood flow (rCBF) in brain regions well beyond M1, including changes found in the right frontal pole, right primary sensorimotor cortex and posterior brain regions. Furthermore, Kwon, Ko & Ahn et al., (2008) found AS of the left M1 to increase activity in the left SMA and right parietal cortex as well. This suggests that tDCS influences cortico-cortical connections (Boros, Poreisz & Münchau et al., 2008) and hence has a widespread effect, the boundaries of which are yet to be clearly defined.

With regards to the method of delivery, there is currently no standardised approach. Research groups vary in the choice of current intensity and duration, the timing of sessions (e.g. single or multiple sessions, timed to occur before, during or after a task) and in the size of electrodes used (see Nitsche and Paulus, 2001 for review). Some labs have explored the use of smaller electrodes to increase the focality of tDCS (i.e. ‘high-definition’ tDCS; Minhas, Bansal & Patel et al., 2010); others have focused on trying to define the spatial distribution of current density using different electrode montages (e.g. Miranda, Lomarev & Hallet, 2006). Despite the variety of methods, none of the studies to date have reported significant side effects of tDCS (Been, Ngo & Miller et al., 2007). This includes research carried out with healthy volunteers or groups of patients with various neurological disorders (Poreisz, Boros & Antal., 2007). The only sensations frequently reported are ‘tingling’ or ‘itching’ felt underneath the electrodes within the first 30-60s of stimulation, and/or a mild headache. This makes tDCS particularly useful for blinding subjects to the condition (Gandiga et al., 2006; Schlaug & Renga, 2008). While there is no evidence for significant negative side-effects of tDCS, larger studies conducted over a longer period of time would be required to rule out the possibility of long-term adverse effects (particularly following multiple sessions).

Overall, tDCS appears to possess the potential to safely stimulate and alter the plasticity of neural structures that could in turn modify human movements. Empirical examinations of the effects of tDCS on motor performance and learning in healthy people (**Sections 7.1.2 & 7.1.3**) and in cases of motor paresis following stroke (**Section 7.1.4**.) are considered in the following sections.

7.1.2 Effects of Transcranial Direct Current Stimulation (tDCS) on Motor performance in Healthy Populations

Transcranial Direct Current Stimulation (tDCS) of M1 modulates cortical activity depending on the polarity of electrode placement (e.g. Nitsche & Paulus, 2001). How this impacts the motor system at the behavioural level has been examined in studies that have paired the intervention with a motor task. Research with young people has found AS to improve contralateral motor performance (i.e. using speed and/or accuracy measures) on tasks such as circle drawing, isometric grip force endurance, finger sequencing, and the JTT (Matsuo et al., 2011; Cogiamanian et al., 2007; Boggio et al., 2006; Vines et al., 2006). Cathodal tDCS, on the other hand, improves performance on the ipsilateral side (e.g. when applied to the left M1, left hand performance was improved; Vines et al., 2006). Vines et al., (2008) also found 'dual-hemisphere' tDCS, whereby AS of the right (non-dominant) M1 and CS of the left (dominant) M1 was delivered simultaneously, yielded an even greater improvement in finger sequencing performance of the non-dominant hand than uni-hemispheric AS of the dominant cortex. This suggests that increasing the activity in one hemisphere directly (i.e. by AS), at the same time as increasing activity indirectly via reduced intracortical inhibition (i.e. by CS), can be even more effective than using either method alone.

While research suggests tDCS can improve measures of motor performance in the younger population, less is known about its efficacy when used with older people, who possess poorer motor skills (e.g. Raw et al., 2012). One recent study found AS to improve JTT performance in healthy older adults – a result which lasted at least 30min post-stimulation (Hummel et al., 2010). It is still unclear what the mechanism of action is for improved motor performance post-tDCS, but the reported improvements seemed to be more pronounced for older participants (e.g. the 87yr-old participant showed the greatest improvement), and on the fine motor subtests of the JTT (*fine motor subtests* = turning cards, grasping small objects, lifting small objects with a spoon; *gross motor subtests* = stacking checkers and lifting light/heavy cans).

Given how important fine motor skills are for continued independent living (and the improved quality of life associated with that; Kim, Warren, Madill & Hadley, 1999), these findings need to be followed up to determine whether this type of tDCS intervention could be widely applied to reduce age-related motoric decline. Crucially tDCS was reported to be well-received by the older participants in Hummel et al.'s (2010) study. Adherence is a major difficulty for medical treatments in general, especially in older patients (e.g. Balkrishnam, 1998), and in rehabilitation medicine where self-treatment regimes require a 'buy-in' from the individual being treated (e.g. compliance to cardiac rehabilitation programs is particularly problematic; Daly, Sindone & Thompson et al., 2002). Even the most efficacious treatment in the lab can only be an effective clinical treatment if the end-user is happy to have the treatment applied.

7.1.3 Effects of Transcranial Direct Current Stimulation (tDCS) on Motor Learning in Healthy Populations

The work cited so far has focused on the effects of tDCS on movement ability – for example movement speed and accuracy. However, in a rehabilitative setting, the goal is often to help patients re-learn movements after an injury (such as stroke). Unlike completing a familiar motor task such as writing or tracing, learning a novel motor skill entails adopting new movement patterns in order to improve performance beyond one's current capacity (Tanaka et al., 2011). Motor learning therefore demands not only the motor processes required to initiate the movement itself, but also a combination of higher-order cognitive processes such as reasoning and memory, which allow a new skill to be retained and retrieved (Rhodes et al., 2004; Voelcker-Rehage et al., 2010). At the neurological level, motor learning entails widespread cortical changes (both structural and functional) that go beyond M1 – a network that includes PM, SMA, cerebellum and basal ganglia (Ungerleider, Doyon & Karni, 2002). Transcranial Direct Current Stimulation (tDCS) could theoretically benefit learning processes in these areas via direct stimulation of a target region beneath an electrode (e.g. M1), but also through its effect on intracortical activation. Boros et al., (2008), for example, found that excitation evoked by AS of the left PM also caused changes in the interconnected ipsilateral M1. This suggests that tDCS may enhance the network of processes involved in motor learning – specifically by increasing activity in the M1 contralateral to the learning limb, or decreasing activity on the ipsilateral side.

Studies that have examined the use of tDCS to enhance motor earning in the healthy population are limited in number, but a couple of recent studies do show a positive effect of the technique (Reis & Fritsch, 2011; Tanaka et al., 2011). A common paradigm used to test the effects of tDCS on motor learning has been the Serial Reaction Time task (SRT). The traditional SRT (Nissen & Bullemer, 1987) requires participants to use four buttons to respond to one of four lights that appear in a repeated or random sequence (i.e. movements made are reflective of real-life tasks such as using a keyboard or mobile phone). A quicker Reaction Time (RT) in the repeated condition indicates learning, whereas a quicker RT for the random sequence reflects general improvements in motor response irrespective of learning (i.e. where planning of movements based on prior experience are minimised). This method, which has been adapted to include temporal, motor and spatial elements (e.g. Shea et al., 2006), therefore provides a means of examining learning online (i.e. within a learning session) and implicitly (i.e. without conscious awareness of learning). Accordingly, Nitsche et al., (2003) reported improved basic RT learning when combined with AS, and Kang and Paik’s (2011) found that uni-hemispheric AS improved SRT learning to the same extent as a dual-hemisphere set-up (i.e. simultaneous AS of left M1 with CS of right M1). Similarly, explicit motor sequence learning in the contralateral hand has been shown to improve with AS, and decrease with CS, when either was applied to the left M1 (Stagg et al., 2011).

In addition to online motor learning, the effects of tDCS on the consolidation of new movement skills ‘offline’ have also been examined. Using a sequential visual isometric pinch task (SVIPT) Reis et al., (2009) found that AS improved between-day performance relative to sham, and the total amount of learning achieved across the 5-day testing period (i.e. both indexed by a combined speed-accuracy measure). However there was no difference between groups in learning on-line (i.e. when participants were tested during tDCS). This suggests that, in this case, the tDCS intervention facilitated learning through its effect on the consolidation processes that occurred between testing sessions. In a rehabilitative setting, this would be particularly beneficial as a greater initial improvement would not necessarily be coupled with faster forgetting. Furthermore, tDCS might also enhance consolidation without the necessity for sleep – Tecchio et al., (2010) found that AS improved sequence learning when applied immediately after the learning task (i.e. where participants were tested before and after tDCS), suggesting a facilitating effect on early consolidation.

In summary, tDCS has been found to enhance motor learning in young adults. However, further studies are required to determine the impact of polarity of stimulation (i.e. AS, CS or both), timing of delivery (e.g. pre, during or post-training) and intensity/frequency of stimulation (e.g. current intensity and multiple vs. single sessions). For example, some studies suggest dual-hemispheric set-ups may be more beneficial (e.g. Vines et al., 2008) whereas others imply dual is no better than uni-hemispheric AS (e.g. Kang & Paik, 2011). Stagg et al., (2011) also found that tDCS led to poorer learning when applied before rather than during the SRT, suggesting that the timing of delivery could be vital to outcome. Most importantly, these findings need to be replicated in the older population. To the author's knowledge, no study has yet assessed whether tDCS can improve motor learning in healthy older people. There is, however, some evidence of tDCS improving motor performance in older people post-stroke. This will be reviewed in the following section.

7.1.4 Transcranial Direct Current Stimulation (tDCS) for the Rehabilitation of Movement After Stoke

The capacity for tDCS to modulate cortical activity could make it a useful tool for altering a dysfunctional network or suppressing maladaptive processes that can occur in the brain as a result of damage (Zimerman & Hummel, 2010). This thesis has examined the issues surrounding motor learning with a particular aim of informing the rehabilitation of movement after stroke, a traumatic brain injury that causes motor paresis in up to 60% of survivors (American Heart Association, 2008). Motor paresis occurs when the motor pathways responsible for the planning and initiation of controlled action are damaged. It is therefore a strong predictor of functional disability as it limits a person's ability to get back to everyday activities such as dressing and bathing (Legg et al., 2009). Even at 6 months post-stroke, complete recovery of motor function is only evident in 11.6% of cases (Kwakkel et al., 2004). Nevertheless, the plasticity of the human brain means that some degree of functional recovery can be achieved through cortical reorganisation (Byrnes et al., 2001). Because tDCS is a neuro-modulator, it could help to encourage such reorganisation (Bolognini et al., 2009; Bastini & Jaberzadeh, 2012; Schabrun & Chipchase, 2011). For example applying tDCS over the M1 in the damaged hemisphere (i.e. to increase activity), and/or CS to the undamaged hemisphere (i.e. to reduce inhibition) could stimulate functional reorganisation when paired with standard rehabilitation practices.

Transcranial Direct Current Stimulation has been shown to improve a range of post-stroke impairments including cognitive, language and visual difficulties (e.g. Floel, Rosser & Miichka et al., 2008; Monti, Cogiamanian, & Marceglia et al., 2008; Ko, Han & Park et al., 2008), yet evidence to demonstrate its efficacy in the motor domain is somewhat lacking. Most studies have involved patients in the chronic phase of stroke (typically left-hemisphere subcortical stroke) with mild-to-moderate motor impairment. Out of this research, seven studies found that AS or CS improved motor performance in stroke patients, (Boggio et al., 2007; Celnik et al., 2009; Fregni et al., 2005; Hummel & Cohen, 2005; Hummel et al., 2005; Hummel et al., 2006; Kim et al., 2009), and improvements lasted for up to 60min after a single session (Kim et al., 2009), or for up to two weeks when tDCS was applied for five consecutive days (Boggio et al., 2007). One study also applied tDCS in the acute phase of stroke to identify whether it could be used in cases of severe motor deficit. After five daily tDCS sessions however, patients showed no significant functional improvement compared to sham (Rossi et al., 2012).

Though the research findings, at least with chronic patients, are promising, there are two common problems within the cited literature. Firstly, participant numbers have been consistently low (min n = 1; max n = 11), and secondly, most of the studies have relied on the JTT, or similar clinical measures like the Box and Block Test (BBT; Mathiowetz, Volland, Kashman & Weber, 1985) as the only outcome measure (Hummel & Cohen, 2005; Hummel et al., 2005; Hummel et al., 2006; Boggio et al., 2007; Kim et al., 2009). Given that JTT scores are based on the speed at which participants complete the subtests correctly, this combined measure of speed and accuracy provides little information on how tDCS affects the individual kinematics of performance (i.e. such as the distinct measures of speed, accuracy and variability etc that can be gained with the use of KineLab tasks). This issue is of particular importance given that groups with motor decline may trade-off speed and accuracy differently as a means of compensating (see **Chapters 2** and **3**). Furthermore, only one study to date has examined whether tDCS can actually accelerate motor learning. Celnik et al., (2009) used a finger-sequencing paradigm and found that tDCS paired with motor training improved learning more than training alone. This effect was even greater when tDCS was combined with Peripheral Nerve Stimulation (PNS), a method that involves applying electrical currents over the damaged extremity itself.

Another issue with the current literature is a paucity of studies examining whether tDCS is effective when combined with another form of physical rehabilitation. Edwards, Krebs and Rykman et al., (2009) found that the excitatory/inhibitory effects of tDCS (as measured by TMS-evoked MEPs) remained stable after training when applied with robot-assisted wrist therapy. Whether tDCS can benefit functional recovery over the course of a longer-term rehabilitation program has not been consistently demonstrated. One proof-of-concept study by Williams et al. (2010) applied tDCS during a Constraint Induced Movement Therapy (CIMT) task that required young adults to complete tasks with the non-dominant hand over a 3hr period with their dominant hand constrained. Those in the active tDCS group showed greater JTT performance than those who received a sham intervention. One research group to adopt a similar approach with stroke patients is Lindenberg et al. (2010), who compared the effects of 5 consecutive days of combined physical therapy and dual-hemispheric tDCS (i.e. simultaneous AS of the affected hemisphere and CS of the unaffected hemisphere), with sham tDCS and physical therapy. Improvements in motor function were significantly greater in the group that received active tDCS (which was apparent even at a one-week follow-up), and these changes were accompanied by increased activation after the intervention in the affected motor regions, as indicated by fMRI results. Similarly, Bolognini et al. (2011), who combined dual-hemispheric tDCS this time with 14 days of CIMT (where tDCS was applied for 40min at the start of the physical intervention), found tDCS to improve movement on measures such as the JTT compared to sham. Improvements were associated with increased cortical excitability in the damaged brain region and a reduction in interhemispheric inhibition between the unaffected and affected hemispheres (measured using TMS and measures of MEP-evoked potentials). Finally, Hesse, Werner & Schonhardt et al., (2007) conducted a pilot study where tDCS was used alongside robot-assisted arm training.

However, only three of ten patients showed improvement, and there was no control group. Furthermore, the on-going placebo-controlled trial (for which the latter pilot study formed the basis) has still not found any significant improvements using combined tDCS and arm training beyond what can be achieved with sham (Werner et al., 2008). Clearly further trials are required in order to elucidate the effects of tDCS in cases of post-stroke paresis and identify its potential as a rehabilitative aid.

7.1.5 Experimental Aims

The following experiments aimed to address two issues that call for further research, which were identified in the former literature review (**Sections 7.1.1** – **7.1.4**). Firstly, while studies with young adults suggest that tDCS can enhance motor learning (Nitsche et al., 2003; Kang & Paik, 2011; Stagg et al., 2011; Reis et al., 2009; Tecchio et al., 2010), this finding has not been examined in a healthy older adult population. Secondly, studies that have examined the effects of tDCS in the context of stroke rehabilitation have predominantly relied upon clinical measures of functional improvement that are much less informative about the nature of the underlying changes than the kinematic methods developed as part of this doctoral work. Objective kinematic analyses, particularly when measuring movement in cases of stroke, are more likely to distinguish between motor recovery and compensatory changes (e.g. Kwakkel et al., 2008; Alberts & Wolf, 2009). Two experiments were designed therefore in order to (i) develop a kinematic motor learning task that would provide an informative means of measuring movement within a clinical context and (ii) identify whether motor learning can be enhanced by tDCS in healthy young and older participants. In Experiment One, young right-handed adults learned a sequence of 32 aiming movements whilst undergoing one of three tDCS conditions; AS of the left M1, CS of the right M1, or sham stimulation. It was predicted that both of the active stimulation conditions should improve learning relative to sham (i.e. AS by increasing excitability and CS by reducing inhibition). In Experiment Two, right-handed older adults completed a similar learning task, where learning was compared between AS of the left M1 and a sham condition.

7.2 Experiment One: Younger Adults

The following sections provide the methodology (**7.2.1**), results (**7.2.2.**) and discussion of findings (**7.2.3**) for Experiment One, which examined the effects of tDCS on motor sequence learning in healthy young adults.

7.2.1 Method

Details of the participants recruited for the study and how medical suitability was determined are provided in **Section 7.2.1.1**. **Section 7.2.1.2** explains how the task was developed and implemented in the lab. The procedure for applying tDCS is described in **Section 7.2.1.3**, followed by the method of analysis in **Section 7.2.1.4**.

7.2.1.1 Participants

Twenty five healthy adults (15 female, 10 male) aged between 21-35 years (mean age = 26.32, *SD* = 4.56) were recruited from an opportunistic sample (NB. this included students from the University of Leeds, staff and congregation of the University of Leeds Chaplaincy, and members of the International Students Club and the Postgraduate Bible Study Group). All participants were right-handed (mean EHI = 91.72; *SD* = 15.18). To determine medical suitably for Transcranial Direct Current Stimulation (tDCS), participants completed a Medical Health Questionnaire (MHQ; see *Appendix C.1* and *C.2*). Participants were not recruited if they (i) had a history of ophthalmological or neurological problems (ii) had experienced faintness, light-headedness, blackouts, severe headaches, unusual heartbeats/palpitations in the last 12mnths, (iii) had ever undergone electro-convulsive-therapy, (iv) were pregnant, (v) had a personal or family history of Epilepsy, (vi) had in the past experienced head trauma with loss of consciousness, (vii) had any metal fragments present in their body (this included previous injury with a metallic foreign body, or a prior engagement in metal grinding), (viii) had a medical device implanted in their head (including any type of bio stimulator, internal electrodes, electronic, hearing aids, eye prostheses, dentures, or any other electrical, mechanical or magnetic implant). Suitable candidates were randomly assigned to one of three conditions based on the nature of brain stimulation to be received; anodal (n = 9), Cathodal (n = 10) or sham (n = 6) tDCS. The University of Leeds ethics and research committee approved this study and all participants gave written, informed consent in accordance with the Declaration of Helsinki.

7.2.1.2 Motor Sequence Learning Task

A motor sequence learning task was created using 'KineLab' (Culmer et al., 2009). The task was similar to the learning task described in Experiment Two of **Chapter 6** (see **Section 6.3.1.2**), however this version was designed specifically to last for the intended 30 minute duration of the tDCS intervention. In order to achieve this, extensive pilot work was carried out with young volunteers, bearing in mind that the task needed to be complex enough for young adults to continue learning progressively throughout (i.e. not hit 'ceiling' performance too early). The level of difficulty was 'fine-tuned' by experimenting with different numbers of elements in the sequence (e.g. learning anything between 10 to 32 movements), changing the number of targets (e.g. moving between four locations, up to eight locations) and modifying the characteristics of the targets (e.g. coloured vs. black and white, letters, numbers, and symbols). The number of trials given to learn the sequence was also tested whereby there were as few as eight or as many as 20 opportunities to learn the sequence. Complexity was finally deemed suitable when the task led to a gradual learning curve with complete sequence learning by the final five trials, around the 30-35minute mark. The resultant task required participants to use a tablet PC and handheld stylus (the same apparatus as described in **Section 2.2.2**) to learn a sequence of aiming movements made with their preferred (right) hand to eight target locations on the screen. Fourteen 'training' and 'test' trials alternated, allowing participants to practice and reproduce the sequence repeatedly (i.e. training trial, then test trial x 14 repetitions = 28 trials in total). Figure 7.1a shows the training trial set-up as it appeared to participants on the screen, with a central white box (height = 25mm; width = 25mm) surrounded by eight ‘target’ boxes (height = 25mm; width = 25mm) containing a different coloured letter of the Greek alphabet (in clockwise order from top centre; purple Phi, orange Xi, green Delta, red Pi, grey Omega, pink Psi, brown Gamma, blue Sigma). In the training trials, one of the eight target letters appeared in the central box for 1 second as a cue for participants to move the stylus to the target box containing the same letter (e.g. move from the centre to the purple Phi in Figure 7.1.1a). After each individual move to a target box, participants returned to the centre, where the next letter in the sequence would appear. There were 32 letters in the sequence which followed the same sequence pattern for every training trial (i.e. the aim was to improve recall of the same 32-move sequence). After each training trial participants were required to reproduce the sequence of moves they had just practiced in the training trial (i.e. move the stylus back-and-forth between the central box and target locations as quickly and as accurately as possible), but without the letters visible on the screen see Figure 7.1b).

There were two main reasons for choosing coloured Greek letters as the targets, rather than using the black-and-white arrows approach previously described in **Chapter 6** (see **Section 6.3.1.2**). Firstly, this version of the task is arguably more reflective of learning in the real-world where we are accustomed to interacting with objects that have a number of salient properties that can vary such as shape, colour, size, location etc. Secondly, it allowed for learning to be examined in a subtly different context to that used previously (see **Section 6.3.1.2/Section 7.3**). Because participants were cued to move to a location using a coloured Greek letter rather than just given a directional cue to move to an empty box, it was possible to test how participants were learning the sequence in this environment. Would participants simply learn a ‘cognitive string’ of colours and/or letters (e.g. “pink Psi, orange Xi etc”) or would they learn the spatial location? Greek letters were chosen (rather than Roman characters) as a convenient set of symbols that would not be trivial to articulate and would not create word-like strings (none of the participants in this study spoke or read Greek - self-report prior to recruitment). It is reasonable to assume, however, that one strategy might be to learn the sequence like the colours of the rainbow, something we can all recall quite easily on cue. Accordingly, to test whether participants were learning the spatial location of the target letters, or instead using some feature characteristic such as shape or colour of symbols, a ‘transfer trial’ was included at the very end of the task. This task prompted participants to recall the sequence on when the symbols inside the target boxes had all been rotated two positions clockwise from their original placement in the training trial set-up (see Figure 7.1c). If participants were learning the spatial locations of the letters, it would be more difficult to reproduce the sequence when their locations changed.

To ensure that participants had a complete understanding of the task, standardised instructions were presented in a series of slides, which included screen shots of the three trial types (similar to Figures 7.1.1a-c), and participants were given the opportunity to practice the different trial types which featured a 16 element sequence different to that used in the experimental task.

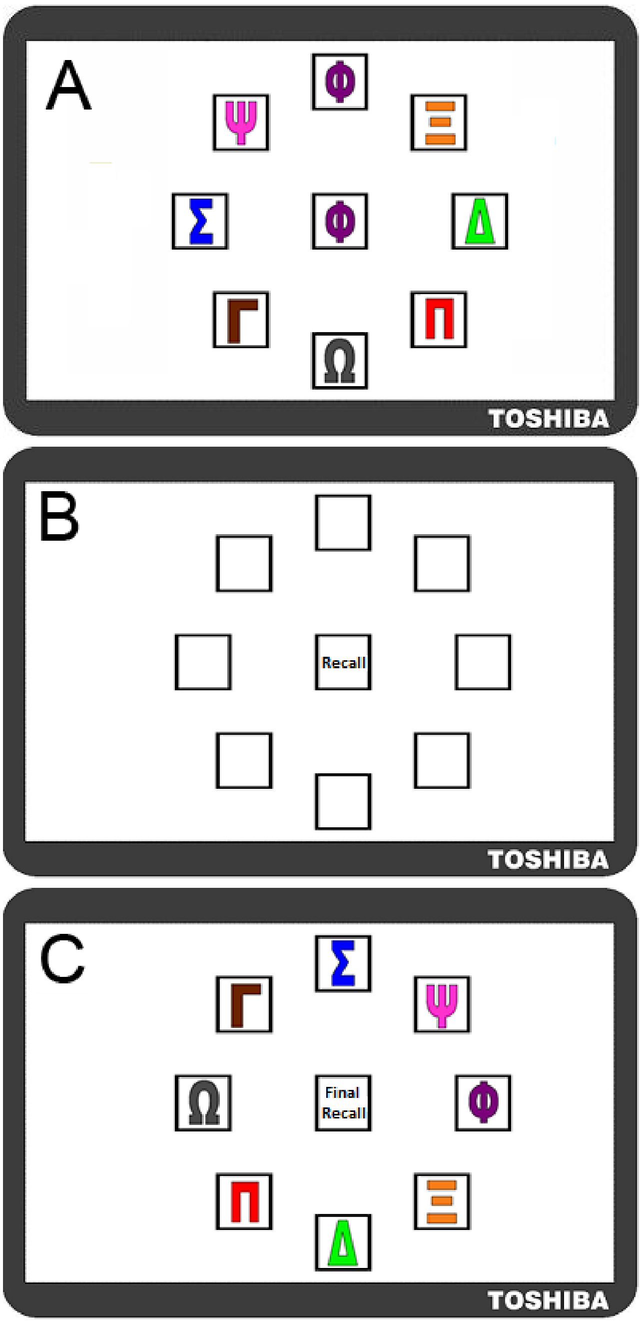

Figure 7.1 *Screen shots of the learning task as it appeared to participants in Experiment One (NB. not to scale).* ***(A)*** *Training trial in which participants moved the stylus into the box corresponding to the Greek letter that appeared in the centre (i.e. purple Phi in this example).* ***(B)*** *Test trial in which participants recalled the pattern of movements they had previously practiced displayed in the training trial, but without the target letters visible on the screen.* ***(C)*** *Final test trial where Greek letters were rotated two positions clockwise from their position in the training trial and participants had to recall the sequence order by moving to new locations on the screen.*

7.2.1.3 Procedure for Transcranial Direct Current Stimulation (tDCS)

Transcranial Direct Current Stimulation (tDCS) was delivered from a battery-powered constant current stimulator (Magstim™ Eldith model) using a set of two rubber electrodes (50 x 50mm) covered with saline-soaked sponges. The stimulator in this study is widely used in labs around the world, has a maximum current of 5,000µA (±1%) and is able to deliver stimulation for up to 30min. For the purpose of this study, a program was set to deliver 30min of constant current stimulation at an intensity of 1.5mA. This included a 'ramp-up' and 'ramp-down' period of 30s (i.e. the current took 30s to gradually increase and a further 30s to decrease at the start and end of the testing period respectively). A 'sham' condition was also programmed to deliver 60s of stimulation at 1.5mA, in between a 30s ramp-up and ramp-down period. While the current intensity could have been set higher at 2.0mA, pilot testing found that 30min of stimulation at this level was uncomfortable for the participant. 1.5mA, on the other hand, was tolerable and did not cause side effects (e.g. irritating itching). The International 10/20 system of electrocute placement was used to locate the brain region of interest depending on the stimulation condition; AS of the left tM1, CS of the right M1, or sham, whereby the positioning of electrodes for AS and CS was counterbalanced across participants. The experimenter was not blinded to the experimental condition. To identify M1, a hypoallergenic medical marker was used to indicate the following points on the scalp; (i) naison to inion, and the halfway point between (the 'Z-line'), (ii) right to left pre-auricular notch, and the halfway point between (the 'C-line), (iii) the vertex (or 'Cz'), where the Z and C lines intersect. Twenty-percent of the C-line measurement was then calculated, and the resultant distance measured outwards from the vertex to the left (for AS) or right (for CS) side of the scalp to mark the target area for stimulation at 'C3' or 'C4', respectively. A reference electrode was also placed above the contralateral supraorbital area (i.e. the part of the forehead above the eye on the opposite hemisphere to the stimulatory electrode). The electrodes were secured with two rubber straps which wrapped over and around the head to ensure optimal contact with the skin (see Figure **7.2**). Once the electrodes were secured in place, additional saline solution was injected into the pre-soaked sponges to optimise the conduction of current and keep impedance below the maximum of 50μA. To ensure that the electrodes remained tight to the scalp and sufficiently soaked throughout the experimental task, participants were not prepped for tDCS until after they had received the instructions for the motor task and completed the practice trials. Participants were also given 30s after the initial ramp-up in order to accommodate to the sensation of tDCS before beginning the task. For the purpose of the motor task, participants were seated at a table with the tablet PC placed at a comfortable distance in front of them.

Figure 7.2 *Young participant with tDCS electrodes placed in preparation for anodal stimulation of the left M1.*

7.2.1.4 Analysis

The aim of this experiment was to establish whether active tDCS would help participants to learn a complex motor sequence, compared to those who received a sham intervention. The following outcome measures were calculated for each 'test' trial:

(i) *Learning measure:* Number of moves recalled in the correct sequential order **(i.e. Correctly Recalled; CR)**, with a maximum score of 32. Points were not deducted for incorrect moves;

(ii) *Recall speed measure:* **Recall Movement Time (MT_r) (s)**, which was the mean time taken to move the mouse from the centre to a target box when recalling the sequence. Because different numbers of moves could be recalled, the MT was calculated per item.

Mean values across the first five trials (F5) and last five trials (L5) were calculated for the two outcome measures and the change in performance provides an indication of learning. A separate mixed-model ANOVA (one each for CR and one for MT_r) was used to compare performance between the beginning and end trial blocks for the three stimulation groups (i.e. anodal, cathodal and sham). The benefit of comparing measures between the F5 and L5 trials is that it shows whether participants were learning progressively (e.g. they did not just learn the whole sequence by trial 3). Differences between the stimulation conditions at the start of the task are more likely to be attributable to group differences (rather than an outcome of tDCS) whereas differences towards the end of the task are more likely to be due to prolonged exposure to tDCS. For the analysis of the transfer trial, in which the spatial positions of the target letters were rotated, two ANOVAs were used to separately analyse CR and MT_r to compare the transfer trial with the final test trial, for the three stimulation conditions. Greenhouse-Geisser estimates of sphericity (ε) are reported for ANOVA results where degrees of freedom have been adjusted.

7.2.2 Results

The following sections provide the results of data analyses for the test trials (**7.2.1.1**), and the transfer trial (**7.2.2.2**).

7.2.2.1 Test Trials

Figure 7.3a displays the proportion (%) of moves recalled in the correct sequential order (CR) across the 14 test trials for the anodal, cathodal and sham stimulation groups. Participants remembered more of the sequence as the trials progressed, and accordingly the ANOVA for CR revealed a significant increase in CR between the F5 and L5 trials (F (1, 22) = 40.41, p < 0.001, c = .65; see Figure 7.4a). There was, however, no main effect of stimulation group, and no trial × stimulation group interaction. This suggests that tDCS had no effect on the number of moves participants were able to recall correctly at test.

Recall Movement Time (MT_r) data demonstrates a gradual increase in the speed at which participants made their moves to targets across the duration of the task (see Figure 7.3b). The MT_r ANOVA showed a significant decrease in MT_r between the F5 and L5 trials (F (1, 22) = 23.9, p < 0.001, η^2_p = .52), suggesting that participants were able to recall the moves faster with practice (see Figure 7.4b). The means for participants in the cathodal (mean MT_r = 1.41s) anodal (mean MT_r = 1.44s) and sham (mean MT_r = 1.49s) stimulation groups were very similar and there was no significant effect of stimulation group and no trial × stimulation group interaction.

7.2.2.2 Recall in the Transfer Trial

In the final trial of the task, participants attempted to recall the sequence on a screen where the target letters were visible, but rotated two positions clockwise from their original location in the training trials (see Figure 7.1c). By comparing CR and MT_r between this 'transfer' trial and the last test trial it was possible to establish whether participants were simply learning the order of letters/colour, or their spatial locations. Two separate ANOVAs to compare CR and MT_r between the last test trial and the transfer trial showed a significant decline in movement speed (i.e. a main effect of trial on MT_r; (F (1, 16) = 17.72, p < 0.05, η^2_p = .53) and accuracy (i.e. a main effect of trial on CR; F (1, 21) = 46.89, p < 0.001, η^2_p = .70) of recall (see Figures 7.5a and 7.5b). There was no effect of stimulation group, or a trial × stimulation group interaction on either of the outcome measures.

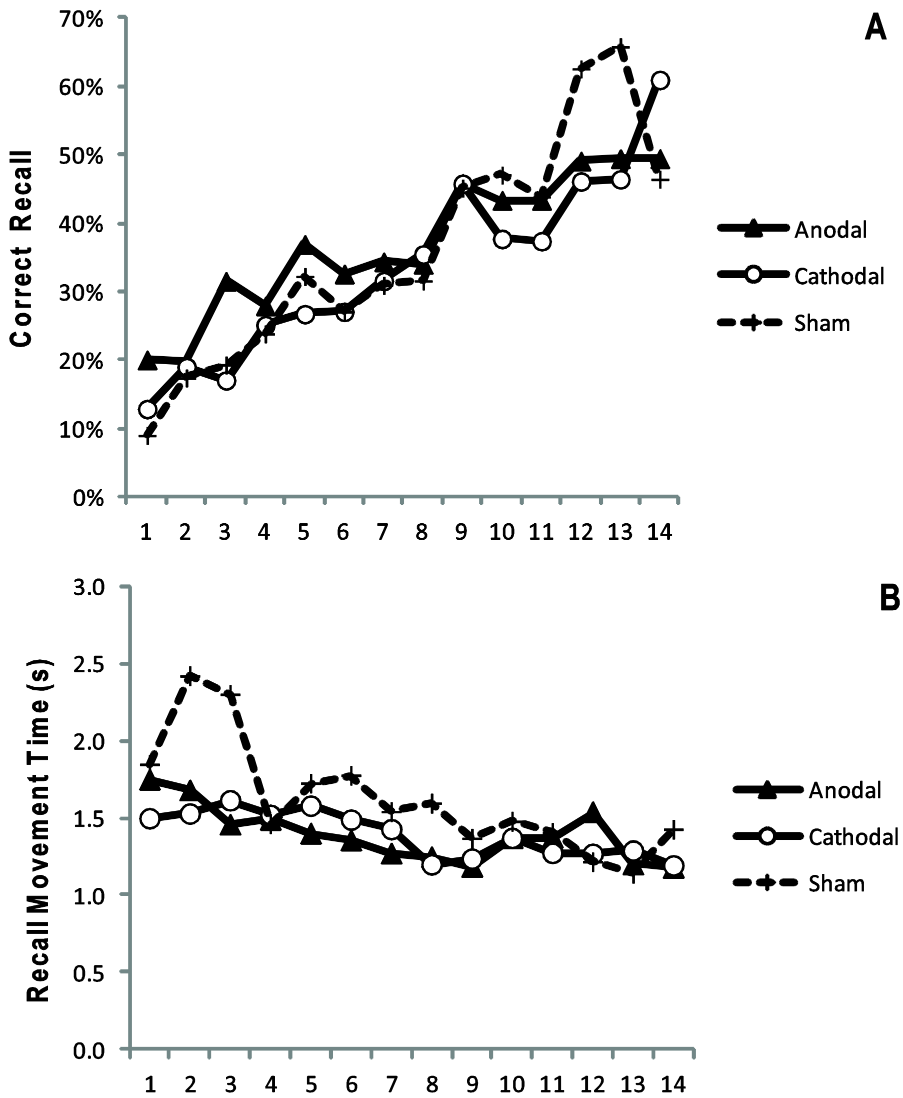

Figure 7.3 *Measurements of motor performance for the anodal (triangles), cathodal (circles) and sham (dashed line, crosses) stimulation groups for each of the 14 test (trials in Experiment One*. ***(A)*** *Proportion (%) moves recalled in the correct sequential order (CR)* ***(B)*** *Mean time taken between moves during free recall (*MT_r*).*

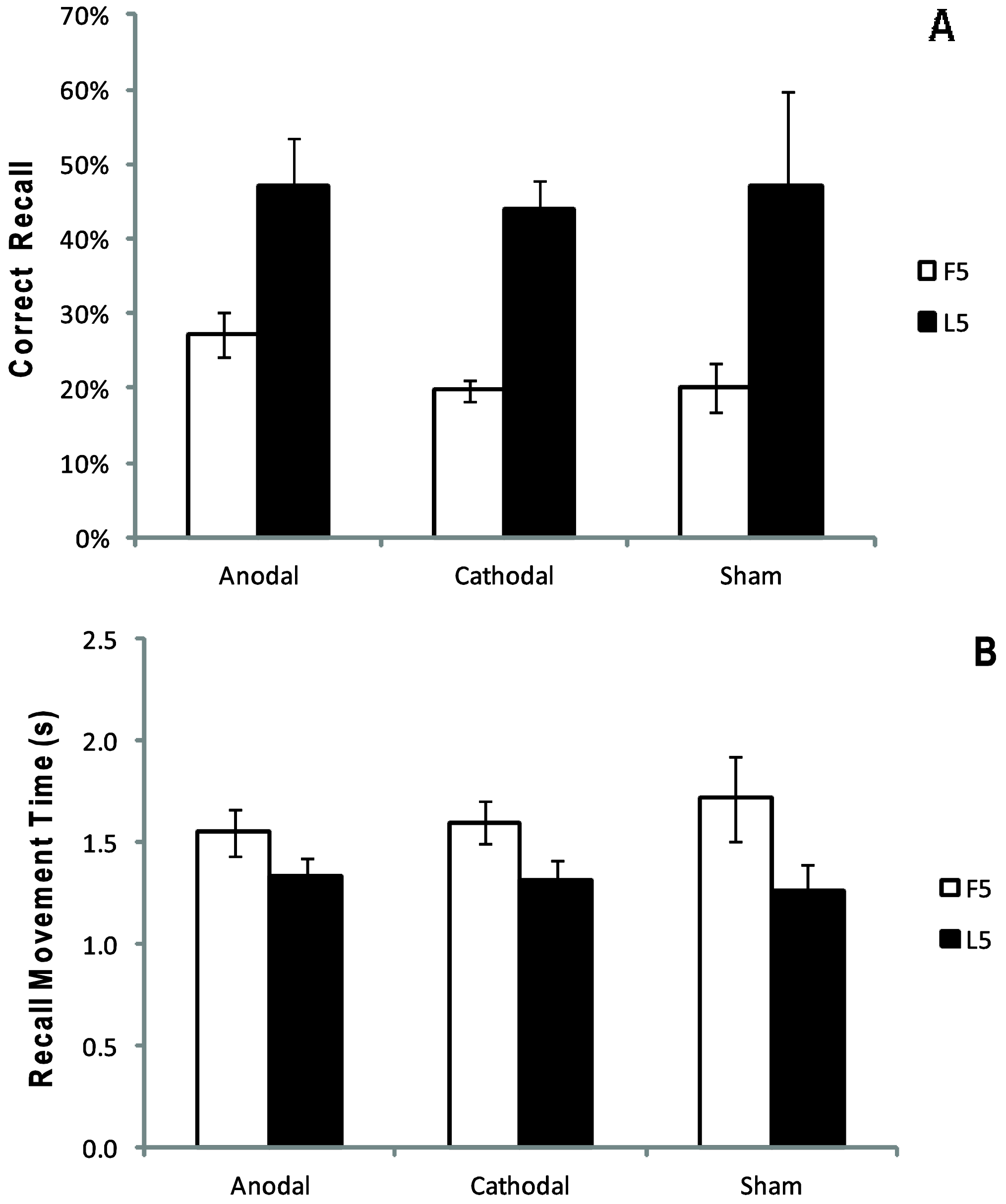

Figure 7.4 *Measurements of performance for the anodal, cathodal and sham stimulation groups averaged across the first five (F5; white bars) and last five (L5; black bars) during the trials in Experiment One.* ***(A)*** *Proportion (%) of moves recalled in the correct sequential order (CR)* ***(B)*** *Mean time taken between moves during free recall (MT_r).*

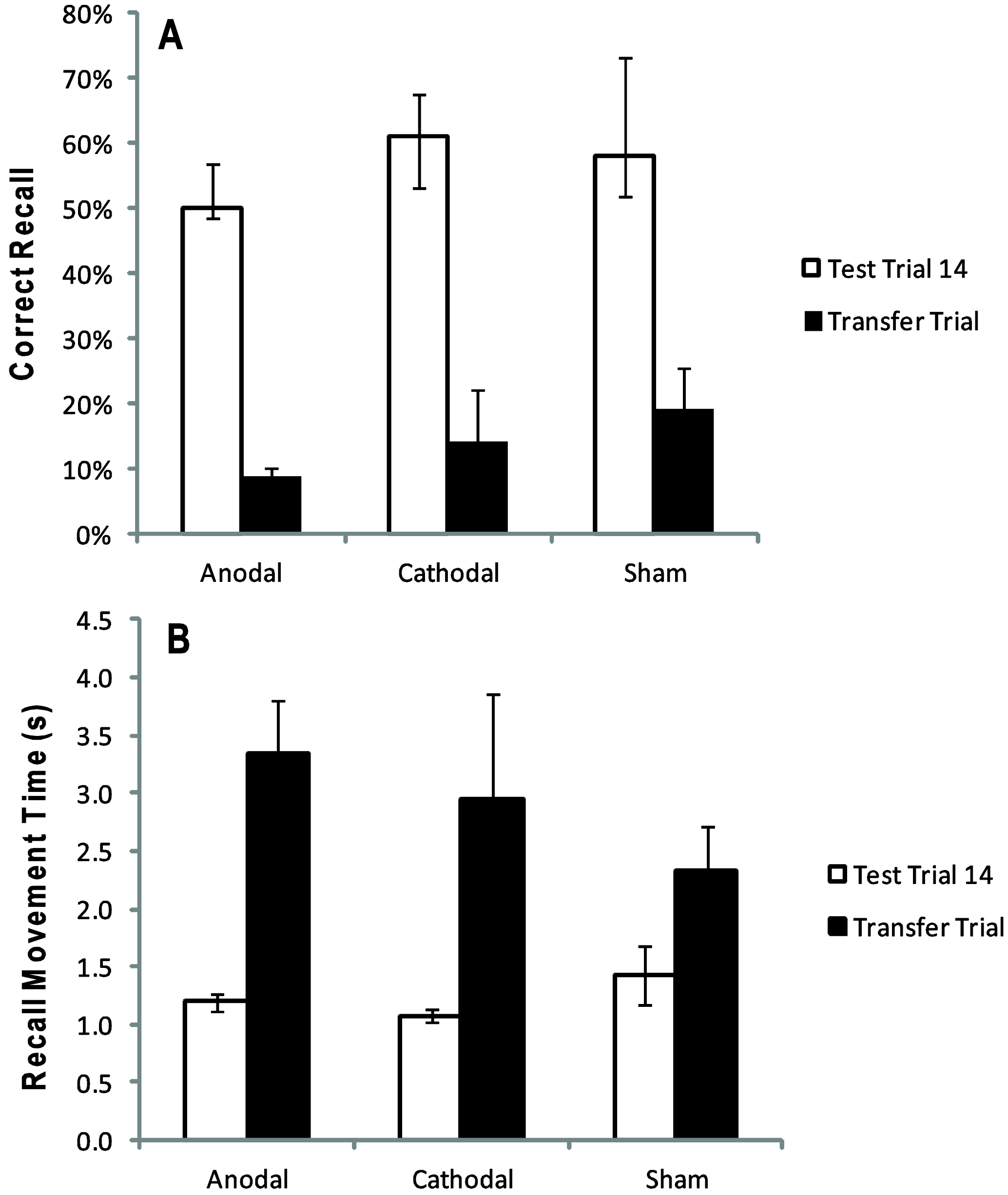

Figure 7.5 *Measurements of motor performance in the last test trial no. 14 (white bars) and the transfer trial (black bars) for the anodal, cathodal, and sham stimulation groups in Experiment One.* ***(A)*** *Proportion (%) of moves recalled in the correct sequential order (CR)* ***(B)*** *Mean time taken between moves during free recall (MT_r). Bars = standard error of the mean.*

7.2.3 Discussion

Participants remembered more of the motor sequence as the task progressed, with around half the moves (i.e. out of the maximum 32) being retained by the final test trial (mean CR for trial 14 in anodal group = 14; cathodal = 19; sham = 14). Participants were also quicker at recalling the moves in the second half of the task (as indicated by lower MT_r values). The poor performance (CR scores dramatically dropped, and MT_r increased) in the transfer trial also suggests that participants were learning the spatial locations of the Greek letters rather than just the order in which the colours/letters appeared.

While all participants showed progressive learning on the task, there was no evidence to suggest that tDCS had any beneficial effect. It had been predicted that both AS (of the left M1) and CS (of the right M1) would result superior performance relative to sham, yet critically there were no significant differences found between the three simulation groups on either of the outcomes measures – no differences in the number of moves recalled correctly and no difference in speed of recall. Again, tDCS also had no impact performance in the transfer trial – all participants appeared to have encoded the sequence spatially (hence no stimulation group × trial interaction found for CR or MT_r when comparing the transfer trial with the final test trial).

One explanation as to why tDCS failed to modify learning in this experiment could relate to the age and skill level of the participant group. Participants were all young well-educated university students (mean age = 26yrs), who should therefore be performing at a high level and already have very good abilities to engage and learn new skills. There may simply have been little room for improving neural plasticity within this population. The lack of effect in the present experiment is also similar to the outcome of the Boggio et al., (2006) study whereby performance of the JTT was improved by anodal tDCS of the right M1 when the non-dominant hand was used, but not when tDCS was applied to the left M1 when the dominant hand was used. The authors attributed this to the fact that 'under-use' of the non-dominant hand in daily life means that the non-dominant M1 can benefit from the additional surge in cortical activation provided by tDCS. Stimulation of the dominant cortex, however, leads to a ceiling effect and no behavioural improvement, as this hemisphere is already optimally activated. The aim of Experiment Two was therefore to examine whether tDCS could improve learning in a population where the dominant cortex may still benefit from an increase in cortical activation – a group of much older participants.

7.3 Experiment Two: Older Adults

Experiment One found that young people were able to learn a complex sequence of aiming movements, improving the number of correct movements and the speed of recall with practice. The tDCS intervention, nevertheless, had no effect on this learning process. Experiment Two therefore used a similar task to examine the effects of tDCS in an older population. Given that no difference was found between the AS and CS groups in Experiment One, Experiment Two only compared the effects of left M1 AS with a sham condition. The next sections provide the methodology, (**7.3.1**), results (**7.3.2**) and brief discussion (**7.3.3**) for this experiment.

7.3.1 Method

Participant details, the motor learning task and the method used to apply tDCS are provided in **Sections 7.3.1.1, 7.3.1.2,** and **7.3.1.3**, respectively. Methods of analysis are discussed in **Section 7.3.1.4**.

7.3.1.1 Participants

Seventeen healthy adults (8 female, 9 male) aged between 60-85 years (mean age = 69.82, *SD* = 8.47) were recruited from an opportunistic sample, which included members of The Cardigan Centre older adult group in Leeds, South Parade Baptist Church and Blenheim Baptist Church. All participants were right-handed (mean EHI score = 96.31, *SD* = 8.48). The MHQ was used to determine medical suitability for tDCS, as outlined in Experiment

One (**Section 7.2.1.1**) Suitable candidates were assigned to one of two brain stimulation conditions whereby participants 1-10 received active anodal tDCS and participants 11-17 were allocated to the sham condition. The University of Leeds ethics and research committee approved this study and all participants gave written, informed consent in accordance with the Declaration of Helsinki.

7.3.1.2 Motor Sequence Learning Task

The same sequence learning task was used as described in **Chapter 6** (see **Section 6.3.1.2**). Participants used a tablet PC and standard computer mouse (i.e. same apparatus as previous experiments) to learn a series of movements made to eight possible target locations on the screen (with their preferred right hand). Fourteen ‘training’ and ‘test’ trials alternated, allowing participants to practice and reproduce the sequence repeatedly (i.e. training trial, test trial x 14 repetitions = 28 trials in total). Figure 7.6a shows the screen as it appeared to participants in the training trial, where there was one central white box (height = 25mm; width = 25mm), surrounded by eight identical ‘target location’ boxes. In the training trials, a black arrow appeared in the central box as a cue for participants to move the cursor to the target location adjacent to the direction of the arrowhead (e.g. top left in Figure 7.6a). After each individual move to a target location, participants returned to the centre, where the next arrow in the sequence would appear (no mouse clicks were required). There were a total of 30 moves to learn, which followed a random pattern. After each training trial, participants were required to reproduce the sequence of moves they had just made in the training trial (i.e. move the cursor back-and-forth between the central box and target locations as quickly and as accurately as possible; see Figure 7.6b). To ensure that participants had a complete understanding of the task, standardised instructions were presented in a series of slides, which included screen shots of the two trial types (similar to Figures 7.6a-b). Participants were also given practices of a training and test trial which featured a 16-move sequence different to that used in the experimental task.

The task lasted between 35-40min and therefore typically occupied participants just beyond the full 30min stimulation period.

There were two main reasons for selecting this particular task rather than repeating the learning task used in Experiment Two (i.e. with Greek letters). Firstly, by using a slightly modified version of the task it was possible to discount the possibility that the lack of tDCS effect identified in Experiment One was related to the nature of the task. For example it is possible that tDCS might just lead to a general increase in arousal and improve task engagement. An engaging task would therefore benefit little from tDCS. Experiment One could be considered relatively engaging with different colours and letters to look at. The arrows version of the task has been designed to be less appealing (i.e. repeated black and white arrows) and so may be less engaging. Secondly, because older adults were to be tested there were concerns it was important to ensure that the visual stimuli were all clearly visible (older adults tend to have some degree of visual impairment) so that performance did not reflect difficulty in recognising the stimuli. .

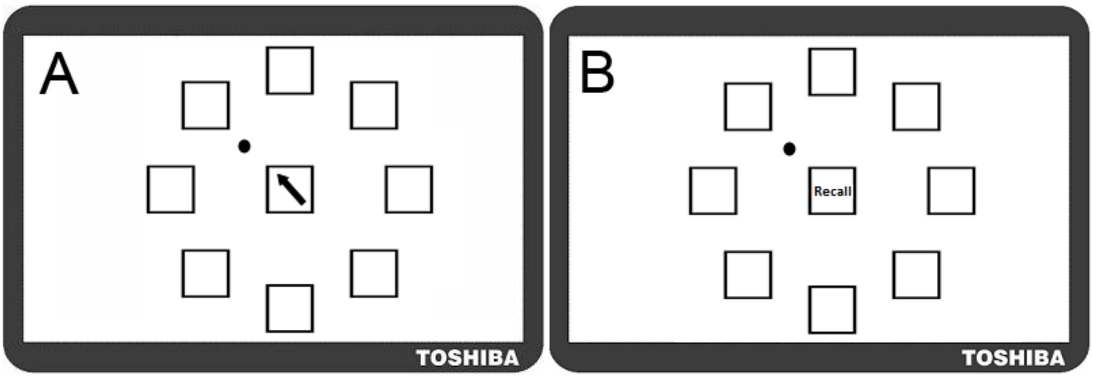

Figure 7.6 *Screen shots of the learning task as it appeared to participants in Experiment Two (NB. not to scale).* ***(A)*** *Training trial in which participants moved the dot according to directional cues that appeared in the central box (i.e. top left pictured).* ***(B)*** *Test trial in which participants recalled the pattern of movements they had previously practiced displayed in the training trial.*

7.3.1.3 Procedure for Transcranial Direct Current Stimulation (tDCS)

The same equipment and protocol for delivery of tDCS was used as outlined in Experiment One (**Section 7.1.2.3**). For anodal stimulation of the left M1, the International 10/20 system was followed to mark the target area on the scalp and a reference electrode placed above the contralateral supraorbital area (NB. this was done after the task was explained and practiced). The experimenter was not blinded to the experimental condition. Anodal stimulation lasted 30min at 1.5mA, which included a 'ramp-up' and 'ramp-down' period of 30sec. In the sham condition electrodes were placed as for anodal stimulation, but the current was only delivered for 60sec, in between a 30s ramp-up and ramp-down period. All participants had 30s after the initial ramp-up in order to accommodate to the sensation of tDCS before beginning the task. Participants were seated at a table with the tablet PC placed at a comfortable distance in front of them and the PC mouse on a mat to their right.

7.3.1.4 Analysis

Outcome measures were identical to those in Experiment One: (i) Number of moves recalled in the correct sequential order out of the maximum of 30 **(CR)**, and (ii): Time taken to move the mouse from the centre to a target box when recalling the sequence **(MT_r)**. Data for these outcome measures were analysed separately whereby mean values for CR and MT_r across the first five trials (F5) and last five trials (L5) were calculated. Separate mixed-model ANOVAs were applied (one for each outcome measure) in order to examine differences in motor learning and speed of recall between the anodal and sham conditions.

7.3.2 Results

Figure 7.7a displays the proportion of moves recalled in the correct sequential order (CR) across the 14 test trials for the anodal and sham stimulation groups. Participants remembered more of the sequence as the trials progressed, which was confirmed by the ANOVA for CR that showed significantly more moves were recalled correctly in the F5 compared to the L5 trials (F (1, 15) = 15.79, p < 0.05, η^2_p = .51). While participants in the sham group recalled fewer moves (mean CR for L5 = 7) than participants who received anodal tDCS (mean CR for L5 = 8), there was no main effect of stimulation group and no trial × stimulation group interaction (see Figure 7.8a).

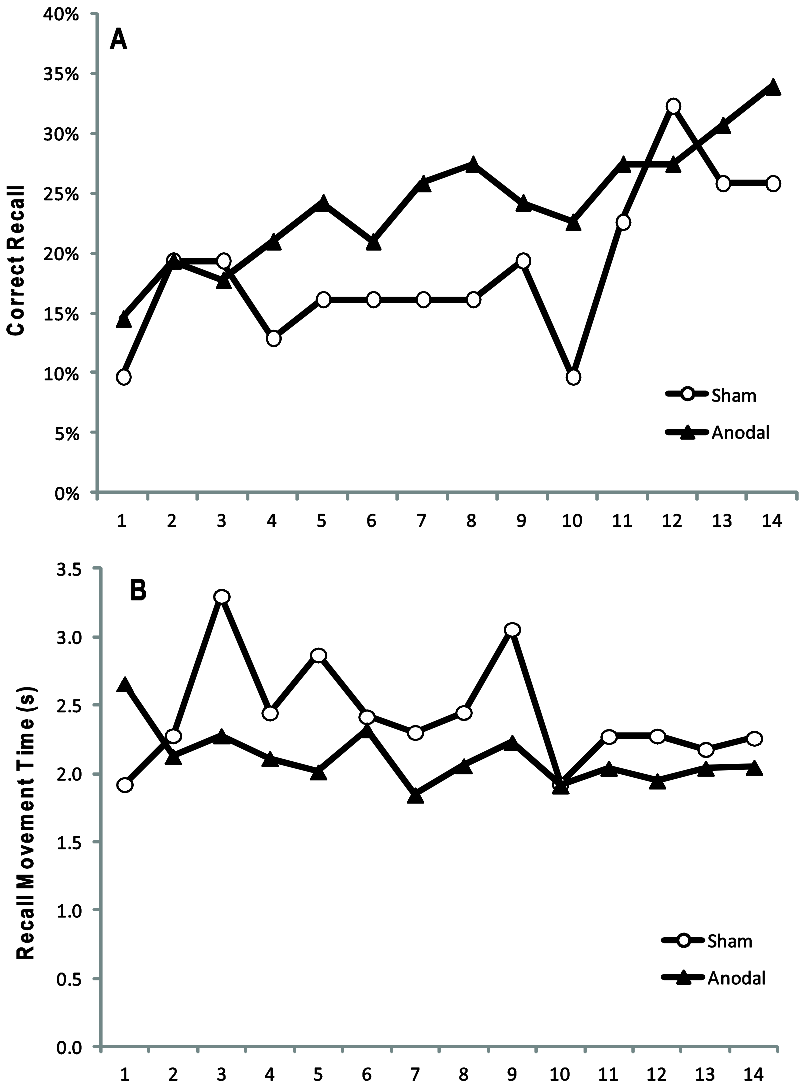

Figure 7.7** Measurements of performance for the anodal (black triangles) and sham (white circles) stimulation groups for each of the 14 test trials in Experiment Two.* ***(A) *Proportion (%) of moves recalled in the correct sequential order (CR)* ***(B)*** *Mean time taken between moves during free recall (MT_r).*

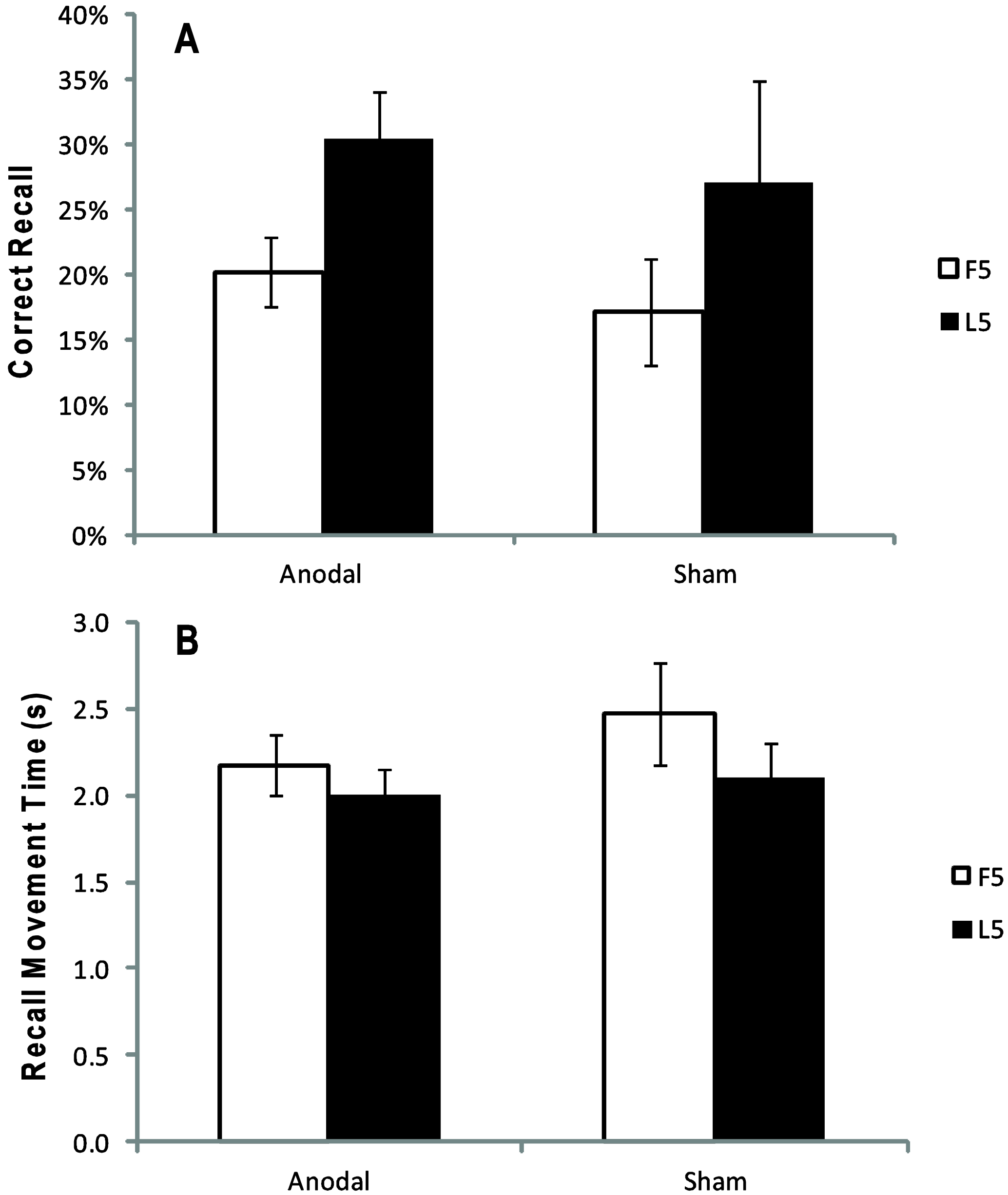

Figure 7.8 *Measurements of performance for the anodal and sham stimulation groups averaged across the first five (F5; white bars) and last five (L5; black bars) test trials in Experiment Two.* ***(A)*** *Proportion (%) of moves recalled in the correct sequential order (CR)* ***(B)*** *Mean time taken between moves during free recall (MT_r). Bars = standard error of the mean.*

Figure 7.7b shows the mean Recall Movement Time (MT_r) across the 14 test trials for the anodal and sham groups. Movement Recall Time improved steadily throughout the task; hence there was a significant effect of trial identified by ANOVA for MT_r (F (1, 15) = 4.94, $p < 0.05$, $\eta^2_p = .25$). On average there was a 0.21s difference in MT_r between the anodal (mean MT_r = 2.08s) and sham groups (mean MT_r = 2.29s), but this was not significant, and there was no trial × stimulation group interaction (see Figure 7.8b).

7.3.3 Discussion

Data analyses revealed that participants learned more of the motor sequence as the task progressed, and were capable of recalling just over one third of the 30-move sequence by the final test trial (mean CR for last test trial in anodal group = 12; sham = 9). Participants also became quicker at recalling the moves by the time it got to the final five trials (i.e. main effect of trial on MT_r).

With regards to the effects of tDCS on learning the results were consistent with Experiment One - there was no clear benefit revealed by either outcome measure. Our prediction based on previous work with younger adults (e.g. Nitsche et al., 2003; Kang & Paik, 2011; Stagg et al., 2011; Reis et al., 2009; Tecchio et al., 2010) was that AS might improve motor learning in older adults by increasing neuronal activity in the left M1. In the present experiment, however, our analyses showed no effect of tDCS on the number of moves older participants recalled correctly, or the speed at which they were able to recall them.

7.4 General Discussion

Transcranial Direct Current Stimulation (tDCS) modulates neuronal activity when applied over the motor cortex (Nitsche & Paulus, 2000; Nitsche & Paulus, 2001; Nitsche et al., 2003a; Nitsche & Paulus, 2011; Jacobson et al., 2012; Jang et al., 2009; Kwon & Jang, 2011; Venkatakrishnan & Sandrini, 2012; Stagg et al., 2009). At the behavioural level, this could lead to improvement of motor performance in healthy groups (Matsuo et al., 2011; Cogiamanian et al., 2007; Boggio et al., 2006; Vines et al., 2006; Vines et al., 2008; Hummel et al., 2010). Studies with younger adults also suggest that tDCS can enhance the processes involved in learning a new motor skill, for example sequence learning (e.g. Nitsche et al., 2003; Kang & Paik, 2011; Stagg et al., 2011; Reis et al., 2009; Tecchio et al., 2010).

While the previous literature appears promising, the evidence base is currently quite sparse and few studies have examined the effects of tDCS on motor learning in groups of older people. One study recently found that AS improved JTT scores in older adults (Hummel et al., 2010), but to the author's knowledge, no study has yet examined whether tDCS can enhance motor learning within this population. Furthermore, in cases where tDCS has been applied in clinical populations (to improve movement in older people after stroke), while reporting a positive effect of tDCS on movement ability (Boggio et al., 2007; Celnik et al., 2009; Fregni et al., 2005; Hummel & Cohen, 2005; Hummel et al., 2005; Hummel et al., 2006; Kim et al., 2009) the studies all rely on similar coarse outcome measures (e.g. JTT or BBT).

The present experiments had two primary aims: (i) develop a kinematic sequence learning task that is suitable for use with healthy people (old and young), that would also be clinically appropriate (i.e. has the potential to provide a more informative outcome measure of learning in patient groups); and (ii) use this task to examine whether tDCS can enhance motor sequence learning in healthy young and older adults, respectively.

The first experiment required young right-handed participants to learn a sequence of 32 aiming movements whilst undergoing one of three tDCS conditions; AS of the left M1, CS of the right M1, or a sham. Though analyses showed a clear learning effect, whereby participants recalled more of the moves correctly, and at a faster pace, as the task progressed, tDCS had no impact on these outcomes. This was the case for both the AS and CS groups, which were both originally predicted to enhance learning (i.e. AS by increasing activity in the left M1 and CS by decreasing activity in the right M1 and reducing intracortical inhibition). The tDCS intervention also had no effect on the way participants appeared to be encoding elements of the motor sequence when learning. In the final ‘transfer’ trial, the location of targets was rotated and all participants subsequently demonstrated a significant drop in speed and accuracy of recall compared to their scores in the final test trial. This suggests that, regardless of the tDCS condition, participants learned the sequence spatially (e.g. top left, top right etc), rather than by using the characteristics of the targets themselves (e.g. pink Psi, orange Xi etc).

In the second experiment, a similar task was used to establish whether tDCS would enhance sequence learning in an older group. It was anticipated that the lack of effect in the first experiment might have been due to the fact that the cortical networks involved in motor learning were already working at their peak in such a healthy young group. Nevertheless, the results of Experiment Two followed an identical pattern to the first experiment – all participants learned more of the sequence, and became quicker at recalling it, as the trials progressed, but with no significant difference between the AS and sham groups. In this experiment it cannot be argued that the task was not difficult enough or that the skill level of the participant group did not necessitate any ‘enhancement’, as even by the end of the task participants were only capable of recalling just over a third of the 30-item sequence. There was therefore plenty of room for improvement, which tDCS did not facilitate.

It seems unlikely that the lack of effect was merely because the stimulation was not sufficiently intense (i.e. not strong enough for sufficient period of time). Most of the previous research with healthy participants applied tDCS for 10-20 minutes with a current of 1-1.5mA, hence the parameters set in Experiments One and Two (i.e. 30min at 1.5mA) were no less intensive than previous experiments that have found tDCS effects (e.g. Matsuo et al., 2011; Cogiamanian et al., 2007; Boggio et al., 2006; Vines et al., 2006; Vines et al., 2008; Hummel et al., 2010; Nitsche et al., 2003; Kang & Paik, 2011; Stagg et al., 2011; Reis et al., 2009; Tecchio et al., 2010). The region of the brain targeted for the placement of electrodes, however, might not have been optimal given the nature of the learning tasks used in this case. Both the Greek Letters (see Figure 7.1) and Arrows (see Figure 7.6) tasks have a strong working memory aspect, whereby elements of the sequence must be temporarily stored and manipulated during the formation of a new long-term representation (Baddeley, 2012; Grafton et al., 1995; Sakai et al., 1998; Unsworth & Engle, 2005). Functional neuroimaging studies show that the DLPFC plays a predominant role in working memory processes (e.g. D'Esposito, Aguirre & Zarahn et al., 1998), and AS of the DLPFC has been found to improve working memory performance using tasks not largely dissimilar to those in Experiments One and Two of this work. For example, two studies presented letters on a screen and asked participants to press a button to indicate whether that letter had been shown three targets previously (a.k.a. the 'three-back letter paradigm') – a task, that while lacking a spatial element, demanded the same working memory processes as the Greek Letters and Arrows tasks (Fregni, Boggio and Nitsche et al., 2005; Ohn, Park & Yoo et al., 2008). The study by Fregni et al., (2005) also showed that although AS of the DLPFC improved performance on the three-back letter task, AS of the M1 did not. The present work might therefore have been more likely to establish a positive effect of tDCS on sequence learning, had the electrodes been positioned over the DLPFC rather than the M1. Of course the principal reason for stimulating M1 was because of interest in the motor learning side of learning rather than improving working memory processes, hence the lack of improvement the present studies suggests that tDCS may not be as suitable for pure motoric deficits.

Given the limited number of studies that have examined the effects of tDCS on motor learning, especially within the older population, it is also important to appreciate the likelihood of 'bottom-drawer effect'. It is uncommon for non-significant results to make it to publication so the scarcity of research could simply be due to the fact that few labs actively investigating tDCS are finding noteworthy effects of tDCS. For example, a search across all of the databases on the metaRegister for Controlled Trials (mRCT), using the keywords 'transcranial direct current stimulation', found 12 active trials that are assessing the effects of tDCS on motor outcomes in stroke patients at present (NB. search conducted October, 2012). Of these 12, only 4 of the research groups have since published findings to suggest that tDCS can enhance movement (e.g. Hummel et al., 2005; Vines et al., 2006 and 2008; Hesse et al., 2007; Lindenberg et al., 2010; Bolognini et al., 2011). Most of the work on the rehabilitation of movement after stroke has also been conducted by the same research group (Friedhelm Hummel and Felipe Fregni being particularly prevalent in this field), and with consistently low patient numbers (NB. one exception is Lindenberg et al., 2010 who had the largest patient group of n = 20).

In rare instances where non-significant results have been published, data suggests tDCS has no benefit and can even make motor symptoms worse in clinical groups – for example in cases of Writer's Cramp or Musician's Dystonia (e.g. Benninger, Lomarev & Lopez et al., 2011; Buttkus, Weidenmüller & Schneider et al., 2010). The potential for tDCS to worsen symptoms, or to have no real benefit beyond treatment as usual, is a clear cause for concern and should be an incentive for authors to persistently seek publication of non-significant findings in the future. It should also inform researchers to apprstimulation groupach with caution the use of tDCS in cases of stroke – both for the sake of the patient (i.e. the possibility of worsening symptoms and using time when another intervention could be applied) and the NHS (i.e. wasting limited resources on a therapy that is not guaranteed to work). Further clarification of whether tDCS can really improve movement without any long-term side effects is clearly the main priority. If such effects cannot be achieved consistently with healthy older adults in laboratory conditions then it is unlikely that this tool would make a useful clinical contribution.

It should also be noted that the tasks developed in the present research provide a novel and informative method of measuring motor learning in older people. The majority of studies with stroke patients in the past have used clinical outcome measures such as the JTT and BBT, which provide a broad measure of motor performance based on how quickly a participant can complete a motor task (e.g. turning cards on the JTT, moving blocks on the BBT). The present tasks, on the other hand, allow the speed and accuracy of movement (as well as other kinematic variables) to be separated out within the same task. The Greek Letters and Arrows tasks for example, record how quickly participants recall elements of a sequence and whether they are recalled in the correct sequential order. Although the present work focused specifically on motor learning, these same tasks can also measure motor performance during the learning trials of the task (see **Chapter 6**). It has already been demonstrated in **Chapter 5** that relying on one outcome measure can lead to effects being missed that are manifest in other aspects of performance. Future research, certainly within clinical settings, should therefore seek to supplement current outcome measures with the addition of kinematic methods such as the sequence learning tasks and other tasks developed as part of this doctoral work (**Chapters 2-7**).

Chapter 8

General Discussion and Future Directions

This chapter begins with a summary of experimental findings from **Chapters 2-7** (**Section 8.1**). Limitations and new questions that arise from that work are considered in **Section 8.2**. The research value and contribution are addressed in **Section 8.3**, followed by a section on future post-doctoral projects (**Section 8.4**). Concluding remarks are made in **Section 8.5**.

8.1 Research Summary

Precise control over the hands and fingers is essential to most tasks of everyday living, but as a consequence of motor decline, older adults find these tasks increasingly difficult to achieve (e.g. Rantenen et al., 1999; Giampaoli et al., 1999). In response to the need for a greater understanding of *how* movement deteriorates with age and whether it can be improved, this doctoral research used novel kinematic technology to examine age differences in motor performance and learning. A series of motor tasks were designed to test hypotheses regarding compensation for motor decline (**Chapters 2** and **3**), manual asymmetries (**Chapters 4** and **5**), motor sequence learning (**Chapter 6**), and the use of tDCS to modify learning in healthy groups (**Chapter 7**).

The tasks that were developed throughout the experimental chapters to assess movement are superior to methods applied previously. Many studies in the past have relied on single outcome metrics or combined measures of speed and accuracy. This can be problematic; especially when examining movement in older groups, where age-related changes in the way participants trade-off speed and accuracy are likely to occur. In **Chapter 2** a path tracing task with different levels of spatial and temporal constraint found that older adults prioritised accuracy over speed and traced closer to the path midline. Tracing closer to the midline is a much ‘safer’ option when motor performance is variable because there is more room for error (i.e. crossing the path boundary). The findings of **Chapter 2** suggest that older people are sensitive to their own level of motor performance and can adjust their motor strategy to minimise error accordingly. But does this apply to other motor tasks? A simulated driving study in **Chapter 3** suggests that it does. The experiment required participants to steer along a series of virtual roads with the same sinusoidal shape, and under comparable spatial/temporal constraints, to the paths used in the tracing study of **Chapter 2**. Under these conditions, similar age differences were observed – older adults applied a ‘middle-of-the-road’ steering strategy, whereas the young preferred to take the ‘racing line’ and cut-the-corners (consistent with previous work: e.g. Mars, 2008; Robertshaw & Wilkie, 2008). Steering trajectories were also more variable in the older group, which suggests that the strategy adopted by older participants was compensatory in nature – more variable steering trajectories were less likely to cross over the road edge when positioned closer to the midline.

The theme of compensation for motor decline was further explored in the experimental work of **Chapter 4**. Research in the cognitive domain suggests that reduced hemispheric lateralisation occurs in the prefrontal ageing brain (i.e. HAROLD; Cabeza, 2002). It has been implied that this change, along with findings from studies where older adults have been seen to recruit additional brain regions relative to the young, is compensatory in nature (e.g. Cabeza et al., 2002). For example, a more bilateral pattern of brain activation in older adults is associated with better performance on cognitive tasks such as memory encoding and retrieval (Cabeza, 2002; Cabeza et al., 1997). Whether the HAROLD phenomenon can be generalised to regions outside of the PFC is, however, unclear. Some neuroimaging studies suggest reduced lateralisation in motor areas (Sailer et al., 2000; Calautti, et al., 2001; Mattay et al., 2002; Ward & Frackowiak, 2003; Naccarato et al., 2006; Heuninckx et al., 2005; Heuninckx et al., 2008), and the concept has been demonstrated at a behavioural level in findings of reduced manual asymmetries in older groups (e.g. Przybyla et al., 2011; Wang et al., 2011).

The latter is exactly the outcome established in **Chapter 4** of this doctoral research, whereby the tracing performance of preferred and non-preferred hands was more similar for older adults than for younger adults. Taken at face value, these findings would imply that HAROLD does indeed take place in the motor system and should hence lead to reduced manual asymmetries when older adults complete any movement task. On the other hand, conflicting findings in the behavioural literature would suggest that older adults can have comparable, or sometimes even stronger, manual asymmetries than the young (Mitrushina et al., 1995; Chua et al., 1995; Francis & Spirduso, 2000; Teixeria, 2008; Goldstein & Shelly, 1981; Weller & Latimer-Sayer, 1985; Dolcos et al., 2002).

An explanation for this conflict in findings might therefore be that performance differences between the hands are much more subtle than widely presumed and are, as a consequence, difficult to measure. The ‘measurement problem’ was explored empirically in **Chapter 5,** which examined age differences in manual asymmetries using a number of different tasks. As predicted, the degree of manual asymmetries observed fluctuated greatly depending on age, the type of task, and the outcome metric chosen to capture performance. On some tasks no performance differences between the hands were identified at all for young or older participants (e.g. manual tracking), yet on other tasks, participants performed better when using their preferred hand (e.g. aiming and tracing).

Furthermore, in a second experiment of **Chapter 5**, the problems that can arise from relying on a single outcome measure when assessing group differences were demonstrated using a tracing task with different levels of spatial and temporal constraint. While a measure of accuracy (i.e. SA) suggested hand, but no age differences, when tracing speed was constrained, a measure of speed (i.e. MT) on a preferred speed version of the task (i.e. where participants paced themselves), revealed both slower tracing in the preferred hand condition, and reduced MTs in the older group. Critically, if accuracy had been the only outcome metric used in this experiment, manual asymmetries would have been missed. When speed was constrained, participants traded speed for accuracy and moved their non-preferred hand slower than their preferred hand, allowing comparable levels of accuracy to be maintained between the two. Overall, what can be concluded from the experimental work of **Chapter 5** is that (i) the process of capturing manual asymmetries relies upon the use of tasks that yield optimal performance with both hands (i.e. complex enough to detect the superior performance of the preferred hand, but without being too difficult that neither hand can perform well); and (ii) conclusions regarding group differences in manual asymmetries should not be based on one outcome metric, as effects can be missed that are manifest in other (unmeasured) aspects of performance. This is particularly important when studying age differences, given that older adults have been found to make distinct spatial and temporal adjustments to their movements in order to compensate for motor decline (**Chapter 2** and **3**).

The focus of experimental work turned to motor learning in **Chapters 6** and **7**, where a sequence learning paradigm was created to examine age differences, and whether learning on the task could be modified using tDCS. In light of the age-related decrements observed in studies of motor performance, it was anticipated that older adults would show poor motor learning. **Chapter 6** tested the hypothesis that there is a relationship between an individual's level of poor motor performance and their ability to learn a new sequence of movements. In the featured task, participants learned a series of 30 aiming movements, a task that may rely on working memory processes to allow elements of the sequence to be encoded, stored and retrieved (e.g. Baddeley, 2012). Because working memory has limited capacity, and motor speed is reduced in older groups, it was predicted that slower motor actions would restrict the number of moves older adults were able to learn. The first experiment, identified poorer motor learning (i.e. fewer moves remembered), and longer movement durations (i.e. during training and test trials) in older participants (similar to previous reports, e.g. Voelcker-Rehage, 2008). In this case, the poorer rate of learning observed in the older group could have been caused by a decline in cognitive ability (e.g. Light & Anderson, 1985; Verhaeghen & Salthouse, 1997), rather than poor motor performance (i.e. movement duration). A further experiment therefore used a within-subjects design to compare learning between the preferred and non-preferred hand, where motor performance was varied within individuals, so that cognitive abilities remained stable (i.e. superior motor performance is expected when using the preferred hand to complete this type of task, see **Section 5.2.2.2**). Subsequent results showed that, while performance and learning was overall worse in the older group, both the young and older adults showed decrements when completing the task with their non-preferred hand – fewer moves were recalled in the correct sequential order, and at a slower pace, when the non-preferred hand was used, regardless of age. This suggests that motor sequence learning is influenced by underlying motor performance, and that reduced motor performance, namely motor speed, can impact negatively on the processes involved in learning beyond the limits imposed by cognitive functions, such as working memory.

The topic of motor learning is also important when it comes to considering motor rehabilitation. In the context of stroke, patients with motor paresis often need to re-learn how to use a damaged extremity and/or adopt compensatory strategies with the unaffected limb. Given the limited resources of the NHS, there is a push towards improving the outcomes of rehabilitation by accelerating the patient recovery while keeping costs low – for example by combining two cost-effective interventions for optimal results. The rehabilitation literature implies that some degree of physical motor training can improve upper limb recovery after stroke (e.g. Ernst, 1990). Whether this outcome could in the future be enhanced with the addition of electrical brain stimulation was a question explored in **Chapter 7**, which specifically examined the efficacy of combining tDCS with a motor learning task. Using variations on the task developed in **Chapter 6**, two studies found that tDCS had no effect on motor sequence learning in either younger or older adults. This outcome was unexpected, as studies have found tDCS to improve motor performance and learning both in healthy and stroke populations in the past (see **Section 7.1**). Limitations of that prior research, nevertheless, include (i) most of the experiments with healthy people have involved younger adults, with minimal replication in older groups; (ii) it is still unclear as to whether the outcomes of tDCS depend on factors such as electrode polarity (i.e. AS, CS or dual-hemispheric), timing of delivery (e.g. pre, during or post-training) and the intensity/frequency of sessions (e.g. current intensity and multiple vs. single sessions); and (iii) studies with stroke patients are few in number, have only involved small groups of chronic phase patients, and have relied upon arguably less sensitive outcome measures than the kinematic tests used within the present doctoral research. Clearly there are many questions that remain regarding the potential for tDCS to improve movement, particularly following stroke. Some of these questions, along with limitations of the experimental chapters are considered in the next section.

8.2 Limitations and Directions for Future Research

This thesis has highlighted some interesting issues on the topics of ageing and motor control, as well as the use of tDCS in the context of movement rehabilitation. Nevertheless, due to constraints on time and cost, some limitations had to be placed on the scope of the experimental work. These limitations can be broken down into four areas, which give rise to questions that should be explored in future research:

(i) *Context of findings*; the majority of experiments for this PhD were carried out in the behavioural labs at University of Leeds Institute of Psychological Sciences. The potential influence of context on experimental findings must therefore be acknowledged. It is indeed possible that older adults respond differently to the young when faced with being ‘tested in a lab’, which could in turn affect performance. Initially this was anticipated to be an issue when recruiting for the tDCS studies, as the sensitive nature of the intervention could have made it more difficult to communicate information regarding safety and comfort within the older community (e.g. older people could perhaps be more wary). Older adults are also at greater risk of motion sickness in virtual reality experiments, which had to be clarified to all participants prior to recruitment for the steering study. While these factors must be taken into account, verbal reports from participants and the author's own interactions with participants in the lab yielded no cause for concern that context-specificity was a problem in any of the studies conducted as part of this doctoral work. To rule out the possibility of context-specific effects, and clarify the extent to which lab-based research affects performance in older and younger groups differently, future research should take advantage of the portable nature of the motor tasks developed in the experimental chapters, and explore testing in different environments (e.g. in community centres or participants' homes).

(ii) *Range of movement explored*; the topic of motor control is undeniably vast, so it was important for the author to 'hone-in' on a specific aspect of this research area and test novel hypotheses that would lead to new findings. Fine motor coordination in the hands and fingers was chosen mainly because it underlies the capacity to independently complete the most basic of daily tasks (e.g. dressing, bathing etc). Moreover, this thesis also aimed to explore the outcomes of tDCS, which has been primarily applied in the context of upper limb movement in the past. While the focus of the present research revealed new insight into the latter topics, an interesting continuation would be to examine whether some of the patterns of behaviour observed would be replicated when a different aspect of movement is considered. For example, in the context of the findings of Chapter 3, are older adults able to make compensatory adjustments to their gait in order to prevent falling?

(iii) *Practicalities of tDCS research*; another limitation relates exclusively to the experimental work of **Chapter 7**. Recruitment for the tDCS studies, both in younger and older groups, was particularly laborious. The slow uptake therefore had an inevitable effect on the hypotheses that could be examined within the timeframe of the PhD. Specifically, the decision was made to restrict testing to one experimental session, rather than observing the outcomes of multiple tDCS interventions. On the one hand this kept participant numbers to an acceptable level; on the other hand, future research must seek to establish whether repetitive tDCS is more likely to yield positive motor outcomes. This is an important issue to address given that the present research found no benefit of tDCS on motor learning when applied only once, during the task itself. Further studies should also experiment with alternative parameters of tDCS – electrode polarity, current intensity and duration of application.

(iv) *Involvement of stroke patients*; The original plan for this research had been to deploy tDCS in a rehabilitation context, but it was considered vital that positive effects of tDCS had been found with healthy individuals prior to testing within a clinical population. This does not mean, however, that this work is not relevant to clinical practice. Having a greater understanding of how movement deteriorates in the case of healthy ageing and the processes that underlie this decline, should inform approaches to rehabilitation in the future. The experimental chapters developed sensitive methods for assessing movement in groups of a similar age to those most susceptible to stroke (i.e. around 60yrs). The next stage for my future research is to implement kinematic methods to improve outcome measures of movement within the context of stroke. This will be achieved as part of a post-doctoral research project for which the author has been granted funds (see **Section 8.4.2**).

8.3 Research Value and Contribution

This doctoral research met its **primary aims** by contributing to our understanding of the effects of healthy ageing on motor performance and learning. Furthermore, the experimental work succeeded in developing a diverse range of motor tasks that can distinguish reliably between poor and proficient movement in healthy groups. In **Chapters 2-5**, the topics of compensation and manual asymmetries were empirically tested. Novel contributions from these studies include evidence that older people apply distinct movement strategies in order to compensate for motor decline, and that manual asymmetries are highly sensitive to measurement, particularly when testing in older populations. Experiments in **Chapters 2** and **3** have subsequently been published in high impact journals (see Raw et al., 2012 and Raw et al., 2012), and the latter work on manual asymmetries is under review. The overriding finding that age influences the way in which an individual adjusts the temporal and spatial parameters of his/her movement, is highly valuable. Firstly, this knowledge will inform future experimental design, so that possible age differences in how participants trade-off speed and accuracy can be taken into account. In the real world, a greater understanding of how people compensate naturally for motor decline is also fundamental to the provision of optimal rehabilitation interventions. A health professional may need to avoid encouraging patients to 'speed up' their movements, if it interferes with a patient's successful strategic compensation. Likewise, in circumstances where suboptimal strategies are being used, individuals should be guided towards an alternative method. For example, if an older person drives too slowly on a busy road, it increases the variance in the speed of vehicles travelling together, which in turn increases the risk of accidents (Garber & Gadirau 1988).

A further aim of this PhD was to examine age differences in motor learning, which was achieved in **Chapters 6** and **7**. **Chapter 6** presented data which suggests that a poor level of motor performance might negatively affect an individual's ability to learn a novel complex motor sequence (Raw, Allen, & Williams et al., submitted). This provides an explanation for the current conflict within the ageing literature, namely that poor learning in older adults varies depending on the task (e.g. Voelcker-Rehage, 2008) – tasks with more demanding motoric elements, are more likely to yield age differences. Can these age differences in motor learning be reduced with tDCS? In **Chapter 7**, the final aim of the thesis was met in two experiments that tested the outcomes of tDCS on motor learning in healthy younger and older adults. While it was found (contrary to prior literature) that tDCS had no effect, this finding is extremely valuable when it comes to considering whether to apply tDCS in clinical groups. Before any intervention is used in the context of stroke, it is crucial that the method is shown to yield replicable outcomes in studies with healthy people. The work of **Chapter 7** highlights essential issues that must be addressed in order to elucidate the real potential for tDCS to benefit motor outcomes. Specifically there is a call for more sensitive methods of assessing movement, which again is something that this doctoral work has provided.

An underlying aim of this doctoral work was to develop motor tasks that will be of value in a clinical setting. Accordingly, some of the author's tasks have already been used to benefit clinical projects (i.e. work not presented in this thesis). For example, the steering task in **Chapter 3** has been used to assess stroke patients presenting with hemianopia and neglect, and the learning paradigm (**Chapters 6** and **7**) has been modified to test the effects of tDCS in children with cerebral palsy. Most importantly, the data collected in **Chapters 2-7** using these tasks has provided the necessary groundwork for securing post-doctoral funds to extend the present PhD project for another year. One grant specifically will allow the author to use KineLab tasks to assess the motor and cognitive outcomes of stroke.

8.4 Future Work

This doctoral research has provided some of the vital pilot work that contributed to two successful grant applications. Both grants will enable the author to apply the KineLab tasks created as part of the present thesis, as well as novel tasks designed to test new hypotheses, in clinical settings. For the first project, described in **Section 8.4.1**, the author will be working as part of a multidisciplinary team to improve methods of assessing motor proficiency in trainee and specialist surgeons. The second project, outlined in **Section 8.4.2**, is funded by a Medical Research Council (MRC) Early-Career Award, granted specifically to the author, who will use KineLab to assess the motor and cognitive outcomes of stroke and surgical stroke procedures.

8.4.1 Understanding Surgical Proficiency and Error

The Leeds Teaching Hospitals Charitable Foundation (LTHCF) has awarded funds for a project titled *'Understanding the Incidence and Nature of Intra-Operative Errors in Minimally Invasive Surgery'*. As part of this project, I will be producing KineLab tasks that can be used to discriminate between poor and proficient performance in surgical professionals. The overriding aim of the research is to gain a greater understanding of the causes of surgical errors, specifically in cases of Minimally Invasive Surgery (i.e. MIS or 'keyhole' procedures), and also to identify methods that have the potential to reduce error in the future. This will be achieved by (i) improving the visuo-motor and tactile feedback available to surgeons during MIS (i.e. identify salient information); and (ii) the provision of training and/or ‘screening’ methods for surgical trainees.

An example of how a KineLab task can be used for latter purposes can be seen in Figure 8.1, which shows data collected in an experiment that compared measures of motor performance between specialist surgeons (n = 10) and non-surgeon young adults (n = 11; all participants aged < 40 yrs; mean EHI = 94.75, *SD* = 9.76), using the Preferred Speed Tracing Task that featured in **Chapter 5** of this thesis (see **Section 5.3.1.2** and **Figure 5.4b**). To clarify, participants used their preferred hand to trace a series of paths that remained the same shape, but varied in thickness (narrow = 2mm; medium = 4mm; wide = 6mm), at their own pace. KineLab recorded mean Shape Accuracy (SA) values, which indicates the extent to which participants deviate from the shape of the path and hence ‘cut-the-corners’ (higher values = lower accuracy, more corner-cutting). Time taken to trace the paths from start to finish was also measured (MT).

An ANOVA on the SA data (Figure 8.1a) showed that path width had the same effect on corner-cutting behaviour as found in the experimental work of **Chapters 2-5** – corner-cutting was greater on the thicker paths (F (2, 38) = 114.20, p < .001, η^2_p =.86). Interestingly, the surgeons (mean SA across all widths = 2.59mm) were also found to cut-the-corners significantly more than the non-surgeon participants (mean SA across all widths for non-surgeons= 1.65mm; F (1, 19) = 143.88, p < .001, η^2_p =.56). A significant thickness ✕ skill interaction (F (2, 38) = 5.19, p < .005, η^2_p =.21) also suggests that the difference in SA between the two groups was even more pronounced in the thick path condition (i.e. surgeons were most likely to cut-the-corner when there was more ‘room for error’ either side of the stylus on the thicker paths). One explanation for the reduced level of accuracy identified in the surgeon group could be that the surgeons prioritised speed over accuracy. Accordingly, the MT data (see Figure 8.1a) shows that surgeons traced at a faster pace than the non-surgeons (mean MT for surgeons across all widths = 13.57s; mean MT for non-surgeons across all widths = 16.17s), which an ANOVA showed was a significant effect (F (1, 19) = 4.84, p < .05, η^2_p =.20). As would be expected, the MT ANOVA also revealed a main effect of path thickness (F (2, 38) = 54.61, p < .001, η^2_p =.74; no thickness ✕ skill interaction) in the expected direction – faster tracing on the thicker paths. Findings such as this could be integral to understanding the variables that mediate poor and proficient motor coordination in surgical trainees and specialists. Could the time pressures of working in the NHS push surgeons to unconsciously adopt strategies that increase the risk of surgical error?

Using variations on tasks like the path tracing task, it will be possible to test further hypotheses regarding the proficiency of motor performance in surgical professionals and between different levels of surgical trainee. The granted funds will also allow for KineLab tasks to be used to establish factors that might contribute to poor performance in a surgical context. For example, the effects of reduced attention/distraction can be easily tested with the motor learning paradigm developed is **Chapters 6** and **7** of the thesis (i.e. it measures motor performance and the cognitive processes necessary for sequence encoding). The fact that the KiniLab system and tablet PC is so portable and user-friendly will mean that outcomes such as how motor performance fluctuates throughout the day, can be assessed despite the demanding schedules of the target population (e.g. medical professionals could administer the tasks on themselves without having to attend a session with a researcher in the lab).

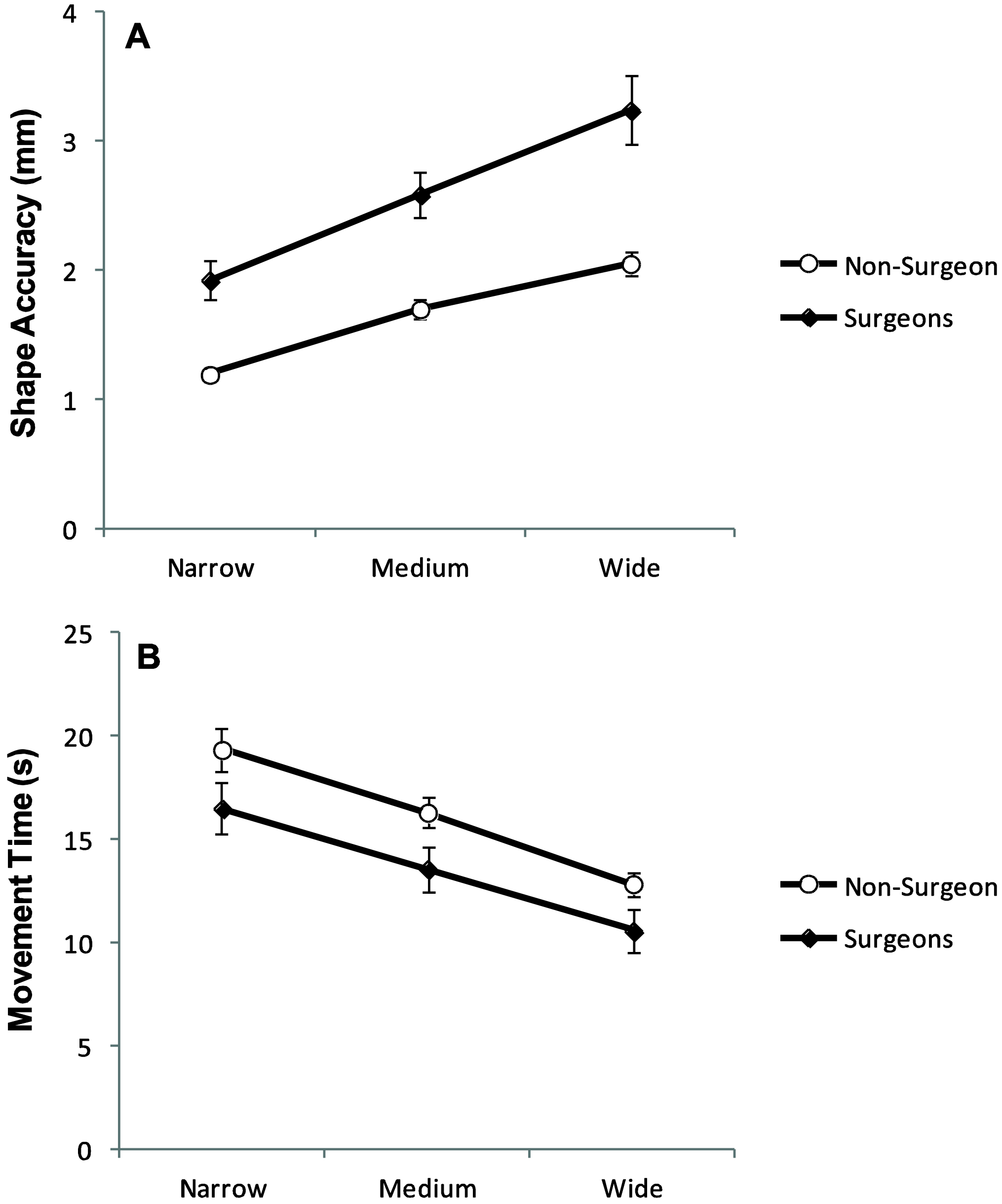

Figure 8.1 *Mean measures of tracing performance for the specialist surgeons (filled symbols) and non-surgeons (open symbols) on the narrow (2mm), medium (4mm) and thick (6mm) paths in the Preferred Speed Tracing Task featured in Experiment Two of* ***Chapter 5 (Section 5.3.1.2)****.* ***(A)*** *Shape Accuracy (mm);* ***(B)*** *Movement Time (s). Bars = Standard Error of Mean.*

8.4.2 Understanding the Outcomes of Stroke and Surgical Stroke Procedures

The **secondary aim** of this doctoral research was to create sensitive methods for assessing motor performance and learning, which have the potential for use in a clinical environment. The LTHCF grant described in the previous section demonstrates how that aim will be met on a post-doctoral project to examine movement in health care professionals. The second grant, on the other hand, is concerned more with understanding and improving patient outcomes directly, specifically in the context of stroke. An MRC Centenary Early Career Award will fund the author’s own project entitled ‘*Understanding the impact of prolonged general anaesthesia on cognition, motor control and learning in patients with Aneurysmal Subarachnoid Haemorrhage (aSAH*)’. The project is timely, as a recent review of the long-term outcomes of aSAH concluded that many questions remain about the cognitive and functional outcomes for survivors (Al-Khindi, MacDonald & Schweitzer, 2010). Only 50% of individuals who experience this type of stroke survive, and the prognosis can be particularly debilitating given that aSAH can occur in someone as young as 40yrs; a time when family and work responsibilities are at a peak (Al-Khindi et al., 2010).

The project will begin by using kinematic tasks to measure the pre and post-operative cognitive and motor outcomes of aSAH. For example, the motor learning task developed in **Chapters 6** and **7** of this thesis will be a useful task for measuring both baseline motor performance and learning in a single testing session. The research also aims to identify the impact of general anaesthesia in surgical procedures used within this particular subgroup of stroke patients. Surgical interventions that can be carried out in order to prevent reoccurrences of aSAH (e.g. aneurysm ‘coiling’ or ‘clipping’), either as an emergency case (i.e. being 'rushed in' to hospital for immediate surgery), or as an elective procedure, inevitably involve a period of time under general anaesthetic. A concern arising in the current anaesthesiology literature is that the use of general anaesthetic (i.e. a medically-induced coma) in stroke patients may exacerbate any cognitive and functional outcomes. Some research suggests this is likely – Davis, Menon & Baghirzada et al. (2012) for example found poorer post-operative outcomes (i.e. assessed by stroke symptom and disability scales) in stroke patients who had endovascular surgery under general rather than local anaesthetic. On the other hand, some RCTs imply no worse effect of general over local anaesthetic on outcome measurers such as quality of life, time spent in acute post-operative therapy and length of stay in hospital (e.g. GALA Trial Collaborative Group, 2008). It will thus be of great value to disambiguate the present conflict in findings by examining the impact of general anaesthetic on the outcomes of aSAH.

8.5 Conclusions

Across a series of nine experiments, this PhD provided evidence of poor motor performance and learning in older adults, as would be predicted from previous research. Novel findings include evidence to suggest older people are sensitive to their level of motor performance and are capable of adjusting their motor strategy to meet task demands and compensate for motor decline. Analyses of manual asymmetries also revealed some age-related changes in the extent to which performance differs between the two hands. One experiment suggests this could be due to an age-related reduction in hemispheric lateralisation, though conflicting results identified under different task conditions imply instead that manual asymmetries are task-specific and sensitive to measurement. Besides age-related changes in motor performance, studies also addressed the effects of ageing on motor learning, which is particularly pertinent to the topic of rehabilitation. A sequence learning task revealed poorer learning in older adults, which could not be improved with the use of tDCS. While no effect of tDCS on learning was identified, the present work highlighted many questions that remain regarding how tDCS should be delivered and outcomes assessed. Future research would therefore benefit from the use of objective kinematic measures, such as the tasks developed within the present thesis. Finally, there is no doubt that the experimental work of this doctoral research has served to produce powerful tests of motor and cognitive abilities that have the potential to revolutionise clinical approaches to older adult care. The use of these measures will be exemplified in the author's funded post-doctoral work, which will examine kinematic outcomes of stroke and surgical stroke procedures.

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Appendix A: Edinburgh Handedness Inventory(EHI) Materials

Sections A.1 and **A.2** are the materials used to complete the EHI.

A.1 Test

Your name:______________________

Your date of birth (DD/MM/YYYY): ________________

Your participant code: ______________

Please indicate with a check (✓) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two checks (✓✓).

If you are indifferent, put one check in each column (✓|✓).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	**Left Hand**	**Right Hand**
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a Box (lid)		
Total checks	**LH =**	**RH =**
Cumulative Total	**CT = LH + RH =**	
Difference	**D = RH – LH =**	
Result	**R = (D / CT) × 100 =**	

A.2 Scoring Instructions

Totaling:

Add up the number of checks in the “Left” and “Right” columns and enter in the “TOTAL” row for each column. Add the left total and the right total and enter in the “Cumulative TOTAL” cell. Subtract the left total from the right total and enter in the “Difference” cell. Divide the “Difference” cell by the “Cumulative TOTAL” cell (round to 2 digits if necessary) and multiply by 100; enter the result in the “Result” cell.

Interpretation (based on results totaled as above):

Below - 40: left-handed

Between - 40 and +40: ambidextrous

Above + 40: right-handed

Full Reference:

Oldfield, R. C., (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, 9(1), 97-113.

Appendix B: Brief Driving History

Name: ___________________

Participant Code (please leave blank): ____________

Please circle your answers to the following questions and provide further details where necessary:

1. Do you currently possess a driving licence? (YES/NO).

2. **If 'YES'**

a. How many miles do you drive per year?

____

b. How many years have you had a driving Licence?

____

3. **If 'NO'**

a. Have you possessed a driving licence in the past? (YES/NO).

b. Please indicate the year you were last in possession of a licence and drove on a regular basis.

____

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Appendix C: Medical Health Questionnaire (MHQ) Materials

Sections C.1 and **C.2** are the materials used to determine eligibility for inclusion in experiments that involved the use of Transcranial Direct Current Stimulation (tDCS).

C.1 Full Medical Health Questionnaire (MHQ)

SURNAME: GIVEN NAMES:

DATE OF BIRTH: SEX:

ADDRESS: WORK PHONE:

HOME PHONE:

1. When was the last time you had a physical examination?

2. If you are allergic to any medications, foods or other substances, please name them.

3. If you have been told that you have any chronic or serious illnesses, please name them.

4. Have you been admitted to hospital in the past three years? Please give details.

5. During the past twelve months (circle **Y/N**):

   (a) Has a doctor prescribed any form of medication for you? **Y/N**

   (b) Have you experienced any faintness, light-headedness, and blackouts? **Y/N**

   (c) Have you had any severe headaches? **Y/N**

   (d) Have you experienced unusual heartbeats such as skipped beats or palpitations? **Y/N**

   (e) Have you experienced periods in which your heart felt as though it were racing for no apparent reason? **Y/N**

6. At present (circle **Y/N**):

   (a) Do you experience sudden tingling numbness or loss of feeling in your arms, hands, legs, feet or face? **Y/N**

   (b) Do you experience pain or discomfort in your chest? **Y/N**

   (c) Do you have diabetes? **Y/N**

7. Have you ever been told that your blood pressure was abnormal? **Y/N**
8. Have you ever undergone electro-convulsive-therapy (ECT)? **Y/N**
9. If you are female, are you pregnant? **Y/N**
10. Have you ever experienced seizures or fainting spells? **Y/N**
11. Have you ever been told that you have any of the following illnesses?

    Myocardial infarcation, arteriosclerosis, heart disease, heart block,

    coronary thrombosis, rheumatic heart, heart attack, aneurism,

    coronary occlusion, angina, heart failure, heart murmur, **Y/N**

12. Has any member of your immediate family been treated for or suspected of having any of the following conditions? Please identify their relationship to you (e.g. father, mother, etc.)

    (a) Epilepsy

    (b) Stroke

    (c) Diabetes

    (d) Heart disease

(e) High blood pressure

(f) Memory loss

(g) Dementia

Y/N

13. Please list all operations or surgical procedures of any kind performed in the last 15 years.

1.
2.
3.
4.
5.
6.

14. Have you ever been injured by any metallic foreign body (e.g. bullet, shrapnel, etc.)? **Y/N**
15. Have you ever (circle **Y/N**)

(a) Engaged in metal grinding? **Y/N**

(b) Could metal fragments be present near your eyes? **Y/N**

16. Is there any history of head trauma with loss of consciousness? **Y/N**
17. Please indicate if you have any of the following (circle **Y/N**):

(a) Cardiac pacemaker **Y/N**

(b) Aneuryism clips **Y/N**

(c) Implanted cardiac defibrillator **Y/N**

(d) Any type of biostimulator **Y/N**

(e) Any type of internal electrodes (e.g. cochlear implant) **Y/N**

(f) Insulin pump **Y/N**

(g) Any type of electronic, mechanical or magnetic implant **Y/N**

(h) Hearing aid **Y/N**

(i) Any type of intravascular coil filter of stent (e.g. IVC filter) Y/N

(j) Artificial heart valve prosthesis? **Y/N**

(k) Orbital/eye prosthesis? **Y/N**

(l) Any type of surgical clip or staple **Y/N**

(m) Intraventricular shunt **Y/N**

(n) Artificial limb or joint **Y/N**

(o) Dentures **Y/N**

(p) Any implanted orthopaedic item (e.g. pins, rods, screws, nails, clips, plates, wire) **Y/N**

(q) Any other implanted item **Y/N**

I certify that the above information is correct to the best of my knowledge. I have read and understand the entire contents of this form and I have had the opportunity to ask questions regarding the information on this form.

Volunteer's name

____ Date:

Volunteer's signature

____ Date:

C.2 Exclusion Criteria for Transcranial Direct Current Stimulation (tDCS)

Individuals were excluded from participation in experiments involving transcranial direct current stimulation (tDCS) if they answered yes to any of the following questions in the MHQ (**Appendix C.1):**

- Question 5b-e.
- Question 8.
- Question 9.
- Question 12a.
- Question 14 (if in the head).
- Question 15b.
- Question 16.
- Question 17 (if in the head or cardiovascular).