Visuo-spatial processing in ageing: neuropsychological and neuroimaging correlates

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Abstract

The relationship between cognitive decline in ageing and changes in associated brain areas is attracting research interest. Growing evidence suggests that in some individuals, recruitment of resources from additional brain areas can act as a buffer against declining cognitive function. However, most research has focused on language while evidence from the visuo-spatial domain is lacking. Categorical and coordinate visuo-spatial relations are known to elicit a marked hemispheric specialisation effect and were therefore utilised to investigate cognitive scaffolding in visuo-spatial processing in healthy ageing.

Two visuo-spatial short-term memory (VSSTM) tasks, the *CATCOORD* task and the *dot-cross* task, were first administered to young adults (n=164) to observe categorical and coordinate performance. Hemispheric lateralisation effects were found in the *dot-cross* task but not the *CATCOORD* task. Neuroimaging results revealed similar bilateral activation when processing categorical or coordinate spatial judgments. Stronger frontal activation was observed when processing difficult coordinate, but not categorical, change trials in the *dot-cross* task.

Seventy-one middle-aged (age between 45-59) and older adults (age above 60) undertook a battery of neuropsychological tests. Some of the older participants (n=38) were recruited to the neuroimaging component of the study. Participants were separated into higher- and lower-performance groups. Neuropsychological results showed widespread correlations between different neuropsychological tests in the lower- rather than the higher-performance group. The young group involved fewer brain regions than the old groups. Within the older participants, the higher performance group activated regions stronger than the lower performance group. In addition, the old-higher performance group showed stronger frontal activations than the young and old-lower groups when processing difficult trials.

Older people showed slower behavioural performance than young people however, no significant difference was observed between the old-higher and old-lower group. A number of interesting findings have been identified to further our understanding of cognitive ageing and scaffolding mechanisms.

Table of Contents

Chapter 1. General Introduction 1

1.1 Outline and organisation of the thesis 1

1.2 Cognition and ageing 3

1.2.1 Attention and executive function in ageing 4

1.2.2 Information processing speed/psychomotor speed in ageing 5

1.2.3 Verbal ability in ageing 6

1.2.4 Memory and ageing 7

1.3 Visuo-spatial processing in healthy ageing and disease 8

1.3.1 Visuo-spatial ability 9

1.3.2 Object-location memory 11

1.3.3 Categorical and coordinate visuo-spatial relations 13

1.4 Ageing theories 15

1.4.1 Hemispheric Asymmetry Reduction in OLD adults (HAROLD), the dedifferentiation hypothesis and the right-hemi ageing hypothesis 15

1.4.2 Posterior-anterior shift in ageing (PASA) 17

1.4.3 The scaffolding theory of ageing and cognition (STAC) 17

1.5 The structure of the healthy ageing brain 19

1.5.1 Volumetric changes 20

1.5.2 White matter integrity 21

1.6 Scope and aims of the project 22

Chapter 2. Development of the CATCOORD task 25

2.1 Introduction 25

2.2 Experiment 1a: CATCOORD task with unicolour, without interference 27

2.2.1 Introduction 27

2.2.2 Methods 28

2.2.3 Results 32

2.2.4 Summary and discussion of Experiment 1a 37

2.3 Experiment 1b: CATCOORD task with unicolour, with/without auditory verbal interference 40

2.3.1 Introduction 40

2.3.2 Methods 41

2.3.3 Results 42

2.3.4 Summary and discussion of Experiment 1b 48

2.4 Experiment 1c: multiple colour, with/without auditory verbal interference 49

2.4.1 Introduction 49

2.4.2 Methods 50

2.4.3 Results 53

2.4.4 Summary and discussion of Experiment 1c 59

2.4.5 Summary of Experiment 1a-1c 60

2.5 Experiment 2: CATCOORD Neuroimaging study 61

2.5.1 Introduction 61

2.5.2 Methods 62

2.5.3 Results 64

2.5.4 Summary and discussion of Experiment 2 71

2.6 Summary of Chapter 2 73

Chapter 3. Development of the dot-cross task 79

3.1 Introduction 79

3.2 Experiment 3: Dot-cross task: A behavioural pilot experiment 81

3.2.1 Introduction 81

3.2.2 Methods 82

3.2.3 Results 85

3.2.4 Exploratory analyses 86

3.2.5 Summary and discussion of Experiment 3 88

3.3 Experiment 4: Dot-cross neuroimaging study 89

3.3.1 Introduction 89

3.3.2 Methods 89

3.3.3 Results 92

3.3.4 Exploratory analysis 95

3.3.5 Summary and discussion of Experiment 4 96

3.4 Summary of Chapter 3 98

Chapter 4. Neuropsychological functions and Ageing 101

4.1 Introduction 101

4.2 Experiment 5: Neuropsychological study of healthy middle-aged and older people 103

4.2.1 Introduction 103
4.2.2 Methods 103
4.2.3 Results 118
4.2.4 Summary and discussion of Experiment 5 166
4.3 Experiment 6: Neuroimaging study in older adults 171
4.3.1 Introduction 171
4.3.2 Methods 172
4.3.3 Results 173
4.3.4 Summary and discussion of Experiment 6 189
4.4 Summary of Chapter 4 193
Chapter 5. General Discussion 197
5.1 Summary of principle findings 197
5.2 Implications of the primary findings 200
5.2.1 Categorical and coordinate spatial representations in VSSTM 200
5.2.2 The ageing study 205
5.3 Strengths and limitations of the current project 209
5.4 Research directions for future work 211
Appendix 215
References 222

List of tables

Table 2-1. Experiment design and methodology comparison between van der Ham et al. (2007) and the current experiment. 39

Table 2-2. Top clusters for the whole brain analysis for the CAT>SAME and COORD>SAME contrasts. 69

Table 2-3. Top clusters for the whole brain analysis for the CAT>Baseline and COORD>Baseline contrasts. 71

Table 3-1. Top clusters for the whole brain analysis for the CAT>COORD contrast. 95

Table 3-2. Top clusters for the whole brain analysis for categorical and coordinate spatial processing. 96

Table 4-1. Inclusion and exclusion criteria for the middle-aged and old-age participants 104

Table 4-2. Neuropsychological battery. 105

Table 4-3. National Adult Reading Test (NART) word list 106

Table 4-4. Neuropsychological results for the middle-aged (n=20) and the older group (n=51). 128

Table 4-5. Spearman correlations between age and the neuropsychological tasks in all participants (i.e. middle-aged and older participants). 129

Table 4-6. Demographic information of OH and OL group. 131

Table 4-7. Means and standard deviations (SD) in the OH and OL group for each task separately and their comparison analysis. 133

Table 4-8. Group effect of OH vs. OL group (including age, NART, and years of education as covariates). 135

Table 4-9. Spearman correlations between the standard neuropsychological tasks in the OH group. 137

Table 4-10. Spearman correlations between standard neuropsychological tasks in the OL group. 138

Table 4-11. Comparisons of the three groups (middle-aged vs. OH vs. OL) for each neuropsychological task. 140

Table 4-12. The group effects of middle-aged, OH, and OL group after covariate with Age, NART, and years of education. 141

Table 4-13. Mean age for middle-aged, old-higher, and old-lower group. 143

Table 4-14. Distributions of higher- and lower-performance group across different age ranges. 143

Table 4-15. Demographic information of the new higher- and lower-performance group. 143

Table 4-16. Pearson correlations between the neuropsychological tasks in the HP group. . 145

Table 4-17. Pearson correlations between the neuropsychological tasks in the LP group... 146

Table 4-18. The final three components generalised via PCA. 148

Table 4-19. Pearson correlation for the CATCOORD task and the neuropsychological components. 149

Table 4-20. Pearson correlation for the higher- and lower-performance group in the CATCOORD task. 149

Table 4-21. Pearson correlation for the 3 principal components and the dot-cross task's performance. 150

Table 4-22. Pearson correlation for the 3 neuropsychological components and RT of the dot-cross task in the higher- and lower-performance groups. 150

Table 4-23. Hierarchical regression for the CATCOORD task ('Group' as a model variable). 153

Table 4-24. Hierarchical regression for the CATCOORD task (higher- vs. lower-performance group). 155

Table 4-25. Hierarchical regression for the CATCOORD task, exploring entry order of background variables (higher- vs. lower-performance group). 156

Table 4-26. Hierarchical regression for the dot-cross task. 158

Table 4-27. Higher- and lower-performance group hierarchical regression for the dot-cross task. 160

Table 4-28. Higher- and lower-performance group hierarchical regression for the dot-cross task (reversed entry of the attention-executive and the STM component). 161

Table 4-29. Higher- and lower-performance group hierarchical regression for the dot-cross task (where the verbal component entry is last). 162

Table 4-30. Hierarchical regression for the HP and LP group with the three cognitive composites where the verbal component entry is first. 164

Table 4-31. Hierarchical regression for the HP and LP group with the three cognitive components where the verbal component entry is last. 165

Table 4-32. Top clusters for the whole brain analysis for the CAT>Baseline and COORD>Baseline contrasts. 176

Table 4-33. Top clusters for the whole brain analysis for the CAT>COORD contrast. 177

Table 4-34. Top clusters for the whole brain analysis for the Young<OH and Young<OL contrast. 181

Table 4-35. Top clusters for the whole brain analysis for the OH>OL and the OL>OH contrast. 182

Table 4-36. Top clusters from the comparisons of the young group and the older groups after the RT modulation. 185

Table 4-37. Top clusters from the comparison of the OH group and the OL group after the RT modulation. 186

Table 4-38. Comparisons of BOLD signal changes between the three groups at the seven clusters (rf. Figure 4-25). 187

List of figures

Figure 2-1. Example stimuli and a trial procedure for CATCOORD task.. 30

Figure 2-2. Mean accuracy of the categorical, coordinate, and same trials with the three encoding times and the three retention intervals...33

Figure 2-3. Mean reaction times of the categorical, coordinate, and the same trial with the three encoding times and the three retention intervals. 34

Figure 2-4. Mean accuracy of (A) categorical- and coordinate-change trials, (B) spatial relations and encoding times, (C) spatial relations and retention intervals, and (D) spatial relations and shift sizes...35

Figure 2-5. Mean reaction times of (A) categorical- and coordinate-change trials, (B) spatial relations and encoding times, (C) spatial relations and retention intervals, and (D) spatial relations and shift sizes...37

Figure 2-6. Mean accuracy of three interference types for the categorical, coordinate, and same condition with the three encoding times 43

Figure 2-7. Mean reaction times of three interference types for the categorical, coordinate and the same condition with the three encoding times 45

Figure 2-8. Mean accuracy of (A) categorical- and coordinate-change trials, (B) spatial relations vs. types of interference group, (C) spatial relations and encoding times, and (D) spatial relations and shift sizes. 46

Figure 2-9. Mean RT of (A) categorical- and coordinate-change trials, (B) spatial relations vs. types of interference group, (C) spatial relations and encoding times, and (D) spatial relations and shift sizes..47

Figure 2-10. Example stimuli and a trial procedure for Exp.1c......................................52

Figure 2-11. Mean accuracy of (A) the four conditions: categorical, coordinate, same, and switched condition, (B) the four conditions with the three encoding times, and (C) the four conditions with the four interference types 54

Figure 2-12. Mean reaction times of (A) the four conditions: categorical, coordinate, same, and switch condition, (B) the four conditions with the three encoding times, and (C) the four conditions with the four interference types. 55

Figure 2-13. Mean accuracy of (A) categorical and coordinate spatial relations, (B) the two spatial relations with the three encoding times, (C) the two spatial relations and the three shift sizes, and (D) the two spatial representations with the four interference types.. 57

Figure 2-14. Mean reaction times of (A) categorical and coordinate spatial relations, (B) the two spatial relations with the three encoding times (C) the two spatial relations and the three shift sizes, and (D) the two spatial representations with the four interference types.58

Figure 2-15. Accuracy of performance for the categorical, coordinate, and same conditions in the CATCOORD neuroimaging study...65

Figure 2-16. Reaction times for the categorical, coordinate and same conditions in the CATCOORD neuroimaging study.. 66

Figure 2-17. Accuracy of performance for the categorical and coordinate conditions with the three shift sizes in the CATCOORD neuroimaging study. 67

Figure 2-18. Reaction times for the categorical and coordinate conditions with the three shift sizes in the CATCOORD neuroimaging study. 68

Figure 2-19. Glass brain images for the contrasts of the categorical or coordinate condition vs. the same condition. 69

Figure 2-20. Contrasts of categorical or coordinate condition vs. baseline (resting state)71

Figure 3-1. All possible dot positions in the stimuli design.. 83

Figure 3-2. Example trial of the dot-cross task. 84

Figure 3-3. Mean accuracy for the dot-cross task.. 85

Figure 3-4. Mean reaction times for the dot-cross task. 86

Figure 3-5. Mean RTs for the first and the last half of the study. 87

Figure 3-6. Mean RTs for categorical and coordinate spatial judgments throughout the study. 88

Figure 3-7. Mean accuracy for the dot-cross fMRI study.. 92

Figure 3-8. Mean reaction times for the dot-cross fMRI study. 93

Figure 3-9. Contrasts of categorical or coordinate conditions vs. baseline 94

Figure 3-10. Contrast of the categorical>coordinate condition 94

Figure 3-11. Glass brain images represent the associated brain activation with longer reaction time. 96

Figure 4-1. An example of a VPT trial. 110

Figure 4-2. An example of a spatial span trial. 111

Figure 4-3. Object memory test. A) Stimuli image: The bottom bar represents timing. B) Response image. 112

Figure 4-4. Visuo-spatial reconstruction task. 113

Figure 4-5. Position-only memory task. The left image is the stimuli image and the right image is the response image. 114

Figure 4-6. Object-location binding task. The left represents the stimuli image and the right represents the response image. 115

Figure 4-7. Combined memory task. The left image is the stimuli and the right image is the response image. 115

Figure 4-8. Line-bisection task. 117

Figure 4-9. Accuracy for the categorical, coordinate, and the same condition for middle-aged and old participants in the CATCOORD task. 120

Figure 4-10. Reaction times for the categorical-changed, coordinate-changed, and the same condition for the middle-aged and the old participants in the CATCOORD task. 121

Figure 4-11. Accuracy of the categorical- and coordinate-changed condition with different shift sizes (20mm vs. 25mm) for middle-aged and older participants in the CATCOORD task. 122

Figure 4-12. Reaction times for the categorical- and coordinate-changed condition with different shift sizes (20mm vs. 25mm) between middle-aged and old participants in the CATCOORD task...123

Figure 4-13. Accuracy for the middle-aged and the old group in the dot-cross task...125

Figure 4-14. Reaction times for the middle-aged and the old group in the dot-cross task. 126

Figure 4-15. Histograms of OH and OL performance for (A) Trail A and (B) ORT:COM.134

Figure 4-16. Accuracy of the dot-cross task during the scan session.. 174

Figure 4-17. Reaction times for the dot-cross task during the scan session. 174

Figure 4-18. Contrasts of categorical or coordinate condition vs. baseline. 175

Figure 4-19. Contrast of the categorical>coordinate condition. 177

Figure 4-20. Accuracy between the young, the old-higher and the old-lower performance group. 179

Figure 4-21. Reaction times for the young, old-higher and old-lower performance group. 180

Figure 4-22. Render brain images represent the whole brain activations during the task for young, OH, OL and the contrast between the OH and OL group.. 181

Figure 4-23. Brain regions that were activated in the young, OH, and OL group in the whole brain analysis 182

Figure 4-24. Render brain images present the associated BOLD signal changes with longer reaction times (i.e. RT modulation) for the young, OH, and OL group and the contrast between the OH and OL group. 184

Figure 4-25. Brain regions showing greater BOLD signal changes in the young, OH, and OL group in long response time trials. 187

Figure 4-26. Combinations of brain activations in the two analyses (i.e. the basic analysis and the analysis with RT modulation) and behavioural performance (RTs). 189

Chapter 1. General Introduction

There is increasing research interest in furthering our understanding of the relationship between cognitive decline in ageing and changes in associated brain areas. Accumulated evidence suggests that older adults with better cognitive performance recruit additional brain resources to ‘scaffold’ age-related decline in cognitive functions. However, most studies which demonstrate ‘cognitive scaffolding’ in ageing focus on the language domain while evidence from the visuo-spatial domain is lacking. The current project aims to observe possible scaffolding mechanisms in older adults via visuo-spatial processing.

1.1 Outline and organisation of the thesis

The thesis consists of five chapters: a general introduction, three experimental chapters, and a general discussion.

The general introduction presents the effects of age in different cognitive domains, including attention/executive functions, information processing speed/psychomotor speed, verbal ability, and memory ability. Although other cognitive abilities, such as sustained attention ability and decision making, are also influenced by age, the presented abilities are selected to illustrate a general picture of age-related cognitive decline. In the second part of the introduction, studies of visuo-spatial ability in healthy participants are discussed. As the current project attempts to observe possible scaffolding mechanisms in ageing via the visuo-spatial domain, longitudinal and cross-sectional studies with healthy participants are reviewed in order to achieve a more comprehensive view of visuo-spatial processing across the lifespan. Studies of patients with cognitive impairments are also reviewed in this section in order to understand cognitive strategies adopted by patients when trying to maintain impaired cognitive functions. Three ageing theories, the theory of hemispheric asymmetry reduction in old adults (HAROLD)/the dedifferentiation hypothesis/the right-hemi ageing hypothesis, the posterior-anterior shift in ageing (PASA), and the scaffolding theory of ageing and cognition (STAC) are introduced in the third part of the introduction. These are representative theories with regard to exploring compensatory mechanisms in ageing. Age-related structural changes in the healthy brain are also briefly introduced in order to achieve better understanding of neurobiological differences in older adults and associations with cognitive behavioural performance. Finally, the scope and aims of the project are provided in the last part of this chapter.

Categorical and coordinate spatial relations are different types of visuo-spatial relations in visuo-spatial short-term memory (VSSTM). Categorical spatial relations describe objects' spatial relations in a broad, abstract manner and usually involve verbal information (e.g. above/below), whereas coordinate spatial relations illustrate objects' spatial relations in a numeric precise manner (e.g. 5mm). The two visuo-spatial relations have demonstrated hemispheric lateralisation effects in abundant literature (Kessels, Kappelle, de Haan, & Postma, 2002; Kosslyn & Chabris, 1992; Kosslyn et al., 1989; Kosslyn, Thompson, Gitelman, & Alpert, 1998; van der Ham & Postma, 2010; van der Ham, van Wezel, Oleksiak, & Postma, 2007). Specifically, better categorical performance is observed if the spatial changes occur on the left hemisphere/right visual field. Coordinate spatial changes are performed better than categorical changes if they are presented on the right hemisphere/left visual field. This characteristic of hemispheric lateralisation may be able to demonstrate a form of scaffolding mechanism in ageing. For example, older adults may recruit bilateral activation during either categorical or coordinate processing. Due to the lack of established visuo-spatial memory tasks in ageing literature, Chapter 2 and Chapter 3 seek a suitable paradigm from existing cognitive tasks with healthy young adults. An appropriate experimental paradigm should be able to demonstrate differences between categorical and coordinate spatial relations and it should also be able to present a form of preservation mechanism in the brain. Chapter 2 presents the development of the first visuo-spatial STM task: the CATCOORD task. A series of manipulations of encoding times, retention intervals, verbal interferences, and shift sizes are examined to investigate their effects on visual-spatial processes (Experiment 1a to Experiment 1c). Experiment 2 is a neuroimaging study which aims to investigate the underlying neural network for the CATCOORD task. The second visuo-spatial STM task, the dot-cross task, is presented in Chapter 3. A pilot behavioural experiment (Experiment 3) and a neuroimaging study (Experiment 4) are included to explore hemispheric lateralisation effects for the two types of spatial relations.

Chapter 4 presents experiments with middle-aged and older adults. Experiment 5 consists of a battery of neuropsychological tests and the two developed visuo-spatial STM tasks with middle-aged and older adults. The neuropsychological battery provides a broad view of cognitive ability in individuals and the two visuo-spatial STM tasks are carried out to compare the performance in different age groups. Some of the older participants are invited to a neuroimaging study in order to investigate the neural network of visual-spatial processing in the healthy ageing brain (Experiment 6). A comparison between the young (Experiment 4) and the older group (Experiment 6) is also performed to explore possible differences in neural networks between different groups.

Chapter 5 is the general discussion, which contains the findings of this project and its contributions to our knowledge about visuo-spatial processing and healthy ageing.

The following sections focus on meta-analysis and review of literature in ageing. Primary resources are presented to extend understanding of topics that are relevant to the current project.

1.2 Cognition and ageing

Age-associated cognitive decline, i.e. healthy ageing (non-pathological, normative cognitive decline), is an important human experience that differs in extent between individuals. There is a large variation in cognitive function in healthy older adults; some of them manage to preserve daily cognitive functions, such as spatial memory and verbal memory, while others show profound decline in their later life. Hedden and Gabrieli (2004) reviewed cognitive abilities that show life-long declines, such as processing speed and working memory, in both cross-sectional and longitudinal studies. Results showed different speeds of age-related decline among cognitive functions. Cross-sectional data from the Seattle Longitudinal Study showed linear declines for information processing speed, episodic memory and spatial ability (Schaie, 1996). Older adults learn new information more slowly than younger adults and they exhibit less efficient reasoning skills (Park, 2000). Moreover, Park and colleagues (2002) demonstrated that on-line capacity of memory, i.e. working memory ability, also declines with age. Older adults showed less storage for memory items than younger adults, whether presented as verbal or visuospatial stimuli. A brief overview of different cognitive abilities and their relationships with age are presented below.

1.2.1 Attention and executive function in ageing

There is a wealth of evidence indicating that cognitive abilities decline with age. While there are many aspects of attention, such as selective attention and sustained attention, and executive functions, e.g. set switching, inhibition, and planning, the following section presents some examples.

Inhibitory functions and ability to switch between tasks are attributed to attention and executive functions, which demonstrate age-related decline. Kray et al. utilised an externally cued task-switching paradigm to examine age-related difference in executive functions (Kray, Li, & Lindenberger, 2002). Participants were required to respond to the stimuli based upon the types of verbal cues provided prior to a trial. For example, the target word "DOG" is characterised as the category of animals, the number of syllables is one, the number of letters is odd, and the word does not contain letter H. The study assessed two components of task switching: general switch costs, which were derived from performance in switch blocks (i.e. different types of task switch were required within a block) and single-task blocks (i.e. one type of task switch was performed in a block), and specific switch costs, which were computed at the trial level, to investigate the difference in performance for a task in which a switch occurs and when a task was repeated. The finding was consisted with the hypothesis, which stated that age-related difference exhibits in specific switch costs. Older adults were slower for switch than for non-switch trials in the four tasks. However, age-related difference in general switch costs occurred only in some tasks and the effects were moderate. It may be due to the design of the experimental paradigm, which allowed upcoming tasks to become predictable. Older adults revealed age-related disadvantages in attention and executive functions, e.g. when task-switching situation could not be foreseen (i.e. specific switch costs).

While age-related decline in executive functions usually accompanies slow response speed, Keys and White (2000) suggest that age alone can account for decline in executive ability. A battery of executive and psychomotor tasks was administered to explore the relationship between executive abilities and psychomotor speed in young and older adults. The results showed that poorer executive performance was related to increasing age. Importantly, even after controlling for psychomotor speed, age still influenced executive performance. The findings indicate that the relationship between age and executive ability is independent of the relationship between age and psychomotor speed. The examples above suggest that age has a unique impact on executive abilities which cannot be attributed to neurophysiological changes, e.g. slow information processing speed.

The Stroop task is a common neuropsychological task to observe selective attention. The task requires participants to name the ink colour in which a word is printed while ignoring the word's identity. Previous literature has demonstrated age-related differences when performing the task (Brink & McDowd, 1999; Milham et al., 2002). Older adults exhibit poor performance when naming the colour of a word (incongruent condition). In addition, older adults showed greater facilitation effects in a congruent condition, when the ink colour and the word is consistent. Milham et al. (2002) utilised fMRI to observe neural networks in young and older participants when processing the Stroop task. Older adults showed less neural activity in dorsolateral prefrontal cortex (DPFC) than young adults when selecting colour information. This region is associated with selective attention, e.g. inhibiting irrelevant information process (e.g. semantic information of a word). Anterior cingulate cortex, which is involved in evaluatory processes of responses (e.g. detecting potential for error), showed increased neural activity in the older group. It is speculated that older adults are likely to increase the ability to process irrelevant representations in working memory. The results provide neuroimaging evidence of age-related changes in selective attention.

1.2.2 Information processing speed/psychomotor speed in ageing

Information processing speed, which is measured by how rapidly people can process new information, shows effects of age. Older adults are known to be slower in making responses/processing new information than young people. Therefore, slow speed of information processing is seen as a process of normal ageing. Salthouse (2000) reviewed research on processing speed variables in older adults. Six different variables were taken into account, including decision speed, perceptual speed, psychomotor speed, reaction time, psychophysical speed, and the time course of internal responses (i.e. neural responses in the brain). These speed variables show strong relations to age with different weights of age-related decline. Overall, increased age is associated with slower responses. Nevertheless, three moderators could alter the relations of age to processing speed, including health status, the amount of experience or practice with the tasks, and characteristics of tasks. For instance, older participants were significantly slower on tasks involving spatial information than tasks involving verbal information (Babcock, Laguna, & Roesch, 1997). Age-related slowness of psychomotor speed is an inevitable process in healthy ageing and may appear in the beginning of adulthood (e.g. age of 20s or 30s). Salthouse (2009) utilised cross-sectional comparisons to investigate age effects on cognitive functions in healthy educated young and middle-aged people (aged between 18 and 60). The results demonstrated that age-related decline occurs relatively early in adulthood, before age 60.

1.2.3 Verbal ability in ageing

It is likely that verbal ability, which includes verbal fluency and verbal comprehension, is less influenced by age compared with other cognitive abilities. Park and colleagues reviewed studies with a broad array of cognitive tasks and found that most non-verbal tasks decline with age (e.g. digit symbol test, pattern comparison test) while verbal tasks, represented by vocabulary tasks, remain relatively steady throughout life span (Park, Polk, Mikels, Taylor, & Marshuetz, 2001b). Similarly, a cross-sectional study with 345 participants and an age range of between 20 and 92 showed a gradual decline in short-term memory containing a visuospatial component or processing-intensive component, such as processing speed (Park et al., 2002). The result for verbal memory revealed relatively steady or even improved performance across life span. This finding suggests opposite effects of age on verbal and visuospatial short-term memory.

There is a relationship between education level and verbal ability. Levels of education are assumed to positively correlate with amount of vocabulary. Verbal ability in healthy adults with more years of education/ higher education level is less likely to be affected by age. Van der Elst et al. utilised a verbal ability related test, Rey's auditory-verbal learning test (Rey-AVLT), to investigate the influence of demographic factors such as age and years of education (van der Elst, van Boxtel, van Breukelen, & Jolles, 2005). A wide age range (age between 24-81) with a large sample size (1855 participants) was used to establish normative data. A significant interaction of age × years of education was found. Older adults who had received more years of education (above 11.4 years) performed better on Rey-AVLT than those who had fewer years of education (around 8.6 years). However, the difference between groups decreased with increasing age. Moreover, different vocabulary tests also reveal different age-related effects. Verhaeghen (2003) conducted a meta-analysis for vocabulary measurements, including standard neuropsychological tasks such as the WAIS, WAIS-R, the Mill-Hill vocabulary scale etc. in older adults from 210 articles. The result showed that performance on multiple-choice tests such as the Mill-Hill vocabulary scale (in which participants are required to choose a synonym) yields greater age advantage than production tasks, e.g. WAIS or WAIS-R. Not all vocabulary tasks show the same proportion of age effects in verbal ability.

1.2.4 Memory and ageing

Memory can be divided into two basic categories: short-term memory vs. long-term memory. Long-term memory can be further separated into semantic memory and episodic memory. Short-term memory stores information on verbal and visuospatial components in a temporary storage and uses central executive functions to moderate information processing (Baddeley & Hitch, 1974; Baddeley & Logie, 1999). Episodic memory refers to the use of language to memorise the when, where, and what of an event. It operates at a conscious level and can be retrieved explicitly. For instance, a type of episodic memory, autobiographical memory, refers to personal experiences which are transferred into long-term storage. Age has different effects on these memory systems. Evidence from a cross-sectional study suggests significant age-related deterioration in episodic memory, while semantic, short-term memory, and perceptual representation systems are relatively preserved (Nilsson, 2003). However, Bopp & Verhaeghen (2005) conducted a meta-analysis of a series of memory span tasks consisting of verbal components, including forward/backward digit span, letter span, word span and so on, and found different results. The results showed that the memory spans of short-term memory and working memory were affected by age. In addition, working memory span is more age sensitive than short-term memory span. The contradictory findings between the two papers may be due to different tasks that were utilised to represent short-term memory. Tasks which reflect the ability to maintain information for a short period (e.g. free recall of words) are less affected by age than those which require simultaneous processing and storage of information, such as verbal memory span tasks. The decreased performance of short-term memory and working memory may be a consequence of declined executive ability in ageing.

Age-related deterioration in memory as well as other cognitive behaviours can be attributed to reduced cognitive capacity or changes in brain structure/function. Rajah and D'Esposito (2005) performed a qualitative meta-analytic review of functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) studies to examine region-specific changes in prefrontal cortex (PFC) function in old age. The two techniques observe neural networks when performing cognitive tasks and age-related differences in brain structures. Studies of working memory and episodic memory with comparisons of young and old adults were included in the analysis. The results showed that both young and old groups engage similar brain regions when performing tasks involving working memory and episodic memory, which suggest that PFC function is maintained throughout age. However, there are age-related region-specific differences in PFC across task domains. For instance, age-related decrease was found in ventral PFC, particularly in the left hemisphere, during working memory and episodic memory encoding tasks (Logan, Sanders, Snyder, Morris, & Buckner, 2002; Madden & Turkington, 1999; Schiavetto, Köhler, Grady, Winocur, & Moscovitch, 2002). However, this region demonstrated age-related increase during retrieval in episodic memory (Anderson et al., 2000; Cabeza et al., 1997; Cabeza, Anderson, Locantore, & McIntosh, 2002; Madden & Turkington, 1999). Age-related increases in left dorsal and anterior PFC are suggested to be functional compensation in ageing (Cabeza et al., 2002; Madden & Turkington, 1999; Reuter-Lorenz et al., 2000). Specific age-related changes in distinct PFC regions in older adults present different correspondent neural mechanisms which are developed with age, and they cannot be solely attributed to the perspectives of functional compensation or dedifferentiation (see section 1.4 for introductions of the notions).

1.3 Visuo-spatial processing in healthy ageing and disease

The previous section addressed age-related decline in different cognitive domains. This section focuses on visuo-spatial ability as the project is designed to investigate possible cognitive scaffolding in older adults via visuo-spatial processes. The first part presents age-related effects on visuo-spatial ability in general. After that, different kinds of visual-spatial processing, particularly object-location memory and categorical and coordinate visual-spatial relations, are discussed. Object-location memory demonstrates the relationship between object identity and position on visuo-spatial representations. The visuo-spatial processing has shown a form of cognitive scaffolding in patient studies (Gallagher, Gray, & Kessels, 2014; Thompson et al., 2006). The current project investigates whether cognitive scaffolding mechanisms can be extended to the older population. The two types of visuo-spatial representations, categorical and coordinate spatial relations, are mentioned in this section as the present project attempts to utilise these two visuo-spatial representations to investigate scaffolding mechanisms with older adults.

1.3.1 Visuo-spatial ability

Spatial cognition includes navigation ability, mental imagery, visuo-spatial perception, visuo-spatial memory and so on. Visuo-spatial ability is considerably affected by ageing, compared to verbal ability. Rosenbaum and colleagues investigated the effect of age difference on remote spatial memory, which is associated with the ability to memorise spatial information/locations to assist oneself in navigating efficiently in new environments (Rosenbaum, Winocur, Binns, & Moscovitch, 2012). Participants underwent a series of visuo-spatial memory tests, including mental navigation tests, recognition of landmarks and locations of these landmarks in a city environment, and the Baycrest route learning test which examines spatial acquisition ability. Older participants revealed significantly poorer performance on the route learning test than young participants. However, performance of the mental navigation tests between the young and the old group was similar. In fact, the old group showed even better performance on some of the navigation tests, which could be a result of a different memory approach. Older participants may verbalise schematic and detailed aspects of the memory items/locations, and memorise them from an objective's perspective. These strategies may result in preserved/better performance in older adults. Similarly, Zakzanis and colleagues (2009) demonstrated that older participants performed more poorly in navigation tasks in a virtual environment than young participants.

There are two types of spatial frames of reference, egocentric and allocentric, in the visuo-spatial domain. Egocentric frames describe spatial information with respect to the body whereas allocentric frames describe spatial information on the basis of external objects (Kosslyn, 1994). Klencklen, Després, & Dufour (2012) reviewed behavioural and neuroimaging studies of spatial cognition in healthy older adults. It is suggested that egocentric and allocentric spatial components showed different vulnerability to age. Broadly speaking, older adults are more impaired on memory tasks related to allocentric than egocentric spatial information. Neuroimaging data shows that different brain regions are involved in both spatial processes. The hippocampus is crucial for supporting allocentric spatial memory/learning (O'Keefe & Nadel, 1978). Egocentric spatial memory/learning is associated with right parietal activity (Galati, Pelle, Berthoz, & Committeri, 2010). Antonova et al. (2009) found reduced activation in hippocampal regions in older adults when performing an allocentric spatial memory task. Moffat, Elkins, & Resnick (2006) utilised a virtual environment task to investigate age differences in allocentric spatial navigation. Older participants showed reduced activation in regions which were crucial for spatial navigation, such as the hippocampus and parahippocampal gyrus, the medial parietal lobe, retrosplenial cortex, bilateral lateral parietal cortex and cerebellum. Overall, age-related decline in allocentric spatial memory is suggested to associate with attenuated hippocampal activation.

Visuospatial impairments are suggested as a sign of dementia and early-onset of Alzheimer's disease; however, distinction of normal age-related deficits and disease-related degeneration is not yet clear. Iachini and colleagues reviewed the role of spatial components in normal ageing, mild cognitive impairment (MCI) and early-onset Alzheimer's disease (AD) in order to identify possible predictors for pathological deficits (Iachini, Iavarone, Senese, Ruotolo, & Ruggiero, 2009). Cognitive performance of MCI is between that of healthy older people and AD patients and is thought to link between normal ageing and pathological impairments. When comparing cognitive performance in a broader scope between healthy ageing and AD patients, the two groups showed different degrees of impairments in central executive resources (e.g. attention or episodic buffer of STM) but no particular indicator is found within the visuospatial domain. However, several indicators have been identified to be predictable for AD or MCI. For instance, Hort et al.(2007) included healthy control, AD patients, older people with subjective memory complaints (SMC),and 3 subgroups of MCI: amnestic single domain (aMCI), amnestic multiple domain (aMCImd), and nonamnestic (naMCI) to investigate their spatial navigation ability. Both allocentric and egocentric components were included in the test. The results showed different patterns of navigation ability impairments among these groups; in particular a specific impairment in allocentric processing was found in the aMCI group. Hence the allocentric component of visuospatial memory is suggested to be a predictor for early on-set AD, which is different from the impairments in MCI.

1.3.2 Object-location memory

Older adults usually complain that they cannot remember the location of things, such as keys. Such memory belongs to ‘object-location memory’, which is important for daily activities and has been broadly studied. When memorising an object, target information (e.g. object’s identity) and contextual information (e.g. ‘when’ and ‘where’ was the target presented) are encoded into episodic memory. Object-location memory involves both target information and contextual information and the ability to bind different types of information. Postma & DeHaan(1996) conducted three experiments to explore short-term memory for object locations. Memory performance for position-only and object-location binding were examined. Participants were required to memorise different types of stimuli (letter vs. nonsense) on a visual array and to reconstruct them at the same positions (with or without clues). The amount of stimuli was also manipulated (7 vs. 10 objects). Articulatory suppression was applied. The number of to-be-remembered targets and articulatory suppression showed different effects for the position-only and object-location binding conditions. The number of to-be-remembered targets affects performance on object-location memory but not position-only memory. Poorer performance was found on object-location memory with increased amount of to-be-remembered targets. Performance of position-only trials remained similar across different numbers of to-be-remembered objects. Articulatory suppression only affected memory performance when object-position binding was required. These differences indicate possible independent processes of encoding/memorising positions and object-to-position binding.

Kessels, Hobbel, & Postma (2007) utilised a computerised object-location memory task to investigate age effects on contextual memory and binding ability. The object-location memory task comprised five experimental conditions: object-only, position-only, position-order, object-order and object-position to examine three types of spatial memory, target memory, contextual memory (positional or temporal feature), and combined memory of the two features. The results showed age effects on all types of memory. Contextual/positional memory, as well as temporal-sequential memory, was more impaired than target memory in older participants. The results demonstrate that some memory features are more susceptible than others in healthy ageing. Specifically, contextual/spatial and temporal-sequential features are more susceptible to age-related decline than memorising target identity. Older adults showed greater binding difficulty than the young, which is thought to be an inevitable result of the ageing process.

Recent neuroimaging evidence also supports age effects on object-location memory. Meulenbroek and colleagues observed performance of object-location memory in young and older adults behaviourally and in an MRI scanner (Meulenbroek et al., 2010). Participants were required to memorise nine objects and their particular locations in a 3×3 matrix which was displayed on a computer screen. During encoding time, some trials presented the nine object pictures simultaneously (i.e. the environmentally rich condition) while other trials presented one clear object picture at a time and the others were blurred (i.e. the environmentally poor condition). Participants were instructed to make a living/non-living judgement on each object to ensure depth of memory process and good recall performance. To distract, a one-back object memory task was performed after the encoding stage. A cued recall was required followed by a rest period. Behavioural results suggested that young adults utilised the information from the environmentally rich encoding structure systematically during retrieval, as using a representation involves mental imagery. However, older participants did not demonstrate such ability. Moreover, neuroimaging results showed stronger activation in the medial temporal lobe and fronto-striatal network in the old group than the young in the environmentally rich condition. Additional recruitment of the fronto-striatal network is speculated as a compensation mechanism in older adults for their reduced attentional resources.

Object-location/contextual memory is impaired in patients after brain tumour resection (Kessels, Postma, Kappelle, & de Haan, 2000) and patients with diencephalic or hippocampal dysfunction (Piekema et al., 2007; Postma, Antonides, Wester, & Kessels, 2008; Postma, Van Asselen, Keuper, Wester, & Kessels, 2006). Patients with Korsakoff's syndrome typically suffer profound episodic memory impairments. These patients also have damage to the frontal lobes and diencephalic regions, which are thought to associate with these impairments. For example, Postma et al. (2006) showed that Korsakoff patients are impaired in processing spatial and temporal information in memory. Kessels and colleagues performed a meta-analysis from 27 patient studies to investigate the relationship between the hippocampal functions and spatial memory (Kessels, de Haan, Kappelle, & Postma, 2001). The results indicate that patients with hippocampal lesions suffer when processing object-location memory, as well as other visuospatial memory tasks. Apart from brain damage patients, patients with affective disorders also exhibit impairments on visuo-spatial memory. Gallagher, Gray and Kessels(2014) utilised an object-location memory (OLM) task to examine visuo-spatial memory processing in bipolar depression patients. Patients and controls underwent the OLM task which consisted of object-identity memory, visuo-spatial reconstruction, position-only memory (POM), Object-location binding (OLB), and combined memory of objects and their positions (COM). An additional battery of neuropsychological tests was administered to profile broader cognitive functions and to further explore the relationship between broader cognitive functions and components of object-location memory. Patients were impaired in the performance of position-only memory, object-location binding, and combined memory tasks. There was a large variation in the object-location binding and combined conditions (i.e. when target identity was presented) among patients. Exploratory analysis found that patients with preserved performance on these processes utilised verbal memory to support/scaffold the impaired visuo-spatial ability. In line with Thompson et al.'s finding (Thompson et al., 2006), additional cognitive resources, i.e. verbal processes in this study, were found to 'scaffold' impaired visual-spatial processes in bipolar depression patients (see the notion of 'cognitive scaffolding' in section 1.4.3).

1.3.3 Categorical and coordinate visuo-spatial relations

There are two types of visuospatial relations between objects in visuo-spatial short-term memory (VSSTM): categorical and coordinate spatial relations. Categorical spatial relations describe objects' spatial relations in abstract verbal terms with a broader manner (e.g. above/below); coordinate spatial relations utilise a more precise and metric manner to describe extra distance between objects (e.g. 5mm). By utilising a computational model, Kosslyn(1987) proposed hemispheric specialisation for processing of the two spatial relations; the left hemisphere is much more efficient in processing categorical spatial relations while the right hemisphere is much more efficient in processing coordinate spatial relations. The hemispheric specialisation for the two types of spatial representations has been explored in numerous studies with different behavioural experimental manipulations(Bruyer, Scailquin, & Coibion, 1997; Jacobs & Kosslyn, 1994; Jager & Postma, 2003; Kosslyn & Chabris, 1992; Kosslyn, Maljkovic, Hamilton, Horwitz, & Thompson, 1995; Kosslyn et al., 1989, 1998). Neuroimaging evidence also supports this notion by demonstrating the lateralisation processes for the two spatial relations in PET (Kosslyn et al., 1998), fMRI (Trojano et al., 2002; van der Ham, Raemaekers, van Wezel, Oleksiak, & Postma, 2009), event-related potentials (ERP) (van der Ham, van Strien, Oleksiak, van Wezel, & Postma, 2010; van der Lubbe, Schölvinck, Kenemans, & Postma, 2006), and repetitive transcranial magnetic stimulation (rTMS) (Trojano, Conson, Maffei, & Grossi, 2006).

Patient studies also support the notion of hemispheric specificity for the two types of spatial relations. Patients with left-hemisphere lesions showed a specific deficit in processing categorical stimuli (e.g. a large cross with more visual information about categorical boundaries) whereas patients with right-hemisphere lesions were impaired in processing coordinate stimuli (e.g. a small cross with less visual information) (van der Ham et al., 2012). Similarly, Palermo and colleagues applied a categorical and a coordinate mental imagery task to investigate the performance of visual-spatial representations in left/right brain damaged patients (Palermo, Bureca, Matano, & Guariglia, 2008). The results showed that the left-hemisphere damaged patients were selectively impaired in processing categorical information while the right-hemisphere damaged patients demonstrated deficits in processing coordinate information. The empirical evidence is in line with Kosslyn's hypothesis which suggests hemispheric lateralisation effects for categorical and coordinate spatial processing. Moreover, the left-hemi damage patients demonstrated the ability to process coordinate spatial representations, indicating that both hemispheres could process either of the spatial relations. The hemispheric difference is a result of varying efficiency in processing categorical and coordinate representations.

Although clear hemisphere lateralisation effects for categorical and coordinate spatial representations have been demonstrated in healthy young participants and patient studies, whether the lateralisation effects persist in later life remains controversial. Bruyer and colleagues contrasted the performance of young and old groups when performing categorical and coordinate tasks (Bruyer et al., 1997). The hemispheric specialisation effect disappeared in the old group. In addition, older participants showed significantly declined performance on the coordinate task but not the categorical task. Coordinate/right-hemi-related spatial representations were more susceptible to age. In contrast, Meadmore, Dror and Bucks (2009) showed the opposite findings in healthy older adults. Older participants were slower in processing spatial information and making spatial judgments yet the characteristic of hemispheric specialisation was suggested to remain consistent in healthy ageing. The inconsistent findings suggest that age-related differences for categorical and coordinate spatial processing are unclear. It is possible that the opposite behavioural results for the two visuo-spatial relations reflect different underpinning neural mechanisms. For example, the disappeared hemispheric specificity in older adults may derive from neural compensation or the dedifferentiation process in ageing (see the notions of cognitive compensation and dedifferentiation in the next section).

1.4 Ageing theories

The above sections have demonstrated age-related effects on different cognitive domains. The following section introduces three common theories in ageing research. These theories are selected as they probe into the relationship between healthy ageing (i.e. with no pathological cognitive deficits) and the brain. They are suitable to examine the hypothesis of cognitive scaffolding in the current project.

1.4.1 Hemispheric Asymmetry Reduction in OLD adults (HAROLD), the dedifferentiation hypothesis and the right-hemi ageing hypothesis

Cabeza (2002) proposed the model of Hemispheric Asymmetry Reduction in OLD adults (HAROLD), which portrays the phenomenon that the two hemispheres exhibit different speeds of age-related degeneration in the ageing brain. Specifically, less lateralised prefrontal activity was found in older adults than in young adults when performing cognitive tasks. Cabeza et al.(2002) observed prefrontal activity in older adults when performing these tasks in order to explore whether the ‘less lateralized’ ageing brain is a result of compensation or dedifferentiation mechanism. Verbal memory tasks, which have been demonstrated with clear right-hemisphere lateralisation effects in PET, were adopted in order to compare brain activity in young versus old groups. In addition, older participants were divided into old-high and old-low groups, in accordance with their performance on a series of memory tasks. Unilateral activations were found in the young group as well as the old-low group. Larger brain regions were activated in right prefrontal cortex in the old-low group compared to the young group, yet they yielded poorer memory performance. This finding implies unsuccessful recruitment of additional unilateral regions for cognitive compensation. The old-high group, on the other hand, showed bilateral prefrontal activity during source memory processing. The additional neural recruitment in left prefrontal cortex indicates a possible compensatory mechanism in older adults with better cognitive performance. Similarly, findings in working memory, visual attention and episodic retrieval demonstrated less lateralised PFC activity in the ageing brain (Cabeza et al., 2004).

There is considerable neuroimaging evidence in ageing literature which shows less specificity or dedifferentiation in brain recruitment when performing cognitive tasks (de Frias, Lövdén, Lindenberger, & Nilsson, 2007; Li & Lindenberger, 1999; Park et al., 2004, 2001b). Older adults recruit more brain areas or exhibit different patterns of neural activation from young adults when performing cognitive tasks. For instance, Park and colleagues demonstrated declined neural specificity in ventral visual cortex in older adults when recognising faces, places, and words. Brain regions which are responsible for processing faces were also more responsive to places in the ageing brain (Park et al., 2004). Neuropsychological evidence revealed similar phenomena by showing more interconnectedness between different cognitive functions in older adults. de Frias et al. (2007) revisited a longitudinal multi-cohort study and found that older participants (aged above 65) exhibited more correlations among various cognitive abilities and increased interindividual differences, i.e. increased individual performance levels are determined by age-related variance in the older groups. The dedifferentiation hypothesis was demonstrated by gradually and constantly increasing correlations among cognitive abilities in old age.

The right-hemi ageing hypothesis states that the right hemisphere is more susceptible to age-related cognitive decline than the left hemisphere (Brown & Jaffe, 1975; Dolcos, Rice, & Cabeza, 2002). Goldstein and Shelly (1981) first noticed different verbal and spatial performance in healthy older people by utilising the Wechsler Adult Intelligence Scale (WAIS). They found performance on tasks with spatial component (which is associated with right hemisphere processing) decreased rapidly in older adults, compared to tasks with the verbal component (which is associated with left hemisphere processing).Evidence from Bruyer and colleagues also showed significant decline in performance of the right-hemi associated coordinate task than the left-hemi associated categorical task. The result indicates that the right hemisphere is more vulnerable than the left hemisphere in old age (Bruyer et al., 1997). Other cognitive domains, such as emotional and sensorimotor processing, also demonstrate more pronounced age-related decline in functions that are attributed to the right hemisphere (Dolcos et al., 2002). Neuroimaging evidence suggests that the right hemi-ageing hypothesis is not contradictory to the HAROLD model. In particular, the HAROLD model accounts for the reduced lateralised prefrontal activity in the ageing brain while the right hemi-ageing hypothesis illustrates the ageing process in other brain regions, i.e. outside of the frontal lobes.

1.4.2 Posterior-anterior shift in ageing (PASA)

Unlike the HAROLD model which proposed bilateral prefrontal activation for cognitive compensation, the PASA illustrates a pattern of cognitive compensation by a shift from posterior to anterior regions in the ageing brain (Dennis & Cabeza, 2008). Davis, Dennis, Daselaar, Fleck, & Cabeza(2008) utilised episodic retrieval and visual perception tasks to investigate age-related changes in brain activity. Older adults presented greater activation in prefrontal regions and weaker activity in occipital regions than young adults. Importantly, better memory performance was positively correlated with increased prefrontal activity and negatively correlated with occipital activity. The age-related increase in anterior brain regions is suggested to be compensation for the age-related deficits in posterior brain activity.

1.4.3 The scaffolding theory of ageing and cognition (STAC)

The scaffolding theory of ageing and cognition (STAC) was firstly proposed by Park & Reuter-Lorenz (Park & Reuter-Lorenz, 2009). It is a conceptual model which proposes that a broad set of cognitive engagement and/or increased neural activity is a result of compensatory mechanisms for declines in cognitive ability in ageing. Older adults recruit more neural resources in frontal regions to maintain the declined cognitive functions. They also involve different cognitive abilities to develop complementary, alternative neural circuits to scaffold age-related neural and functional decline. This scaffolding mechanism reflects a dynamic process of an adaptive brain.

Reuter-Lorenz and colleagues adopted a verbal and a spatial short-term memory task to investigate frontal activity between young and older adults using PET. The two groups showed similar memory performance on both tasks. Importantly, PET results showed different activation patterns in anterior regions between the two groups. The young group revealed lateralised activations while processing verbal and spatial memory tasks whereas the older group showed bilateral activations in frontal regions. The broader neural network observed in the older group was suggested to be ‘compensatory scaffolding’ for age-related decline (Reuter-Lorenz et al., 2000). Similarly, Cappell, Gmeindl, & Reuter-Lorenz (2010) applied event-related fMRI to observe activations in dorsolateral prefrontal cortex (DLPFC) in young and older adults when processing verbal working memory tasks. Three levels of memory loads, depending on the number of letters, were manipulated. The results showed similar behavioural performance on lower memory loads between young and old. However, more over-activations in right DLPFC activation were found in the old group than the young group. In contrast, older participants revealed under-activation in right DLPFC at the highest memory load and their memory performance was significantly poorer than the young group. The stronger neural activity in right DLPFC in the old group reflects an attempt at functional scaffolding for age-related decline.

The majority of studies demonstrating preservation mechanisms in ageing utilise language/verbal tasks, which are associated with prefrontal cortex activation. However, evidence of compensatory processes in other brain regions is limited. Huang et al. (2012) utilised tasks that are associated with posterior parietal activations to investigate preservation mechanisms in older adults. Two Stroop-like tasks were adopted; the number magnitude task is specialised to right-hemisphere process whereas the physical size task is considered to be left-lateralised in the parietal in young adults. A contralateral finding of parietal recruitment was found in older participants: more left parietal activity was found when processing the numerical judgments and more right parietal activation was found during physical size judgments. Moreover, additional posterior parietal and left prefrontal recruitments were found to be associated with better performance in older adults. This finding suggests that age-related bilateral activities are not restricted to prefrontal cortex. An age-related compensatory recruitment was also found in posterior parietal regions. However, no other evidence has been found to support this finding with other cognitive tasks.

Patients with affective disorders also demonstrate impairments of cognitive functions. There are deficits of attention and executive functions, visuospatial abilities, and other cognitive domains, such as short-term memory, long-term memory and psychomotor ability, in euthymic bipolar disorder patients (Robinson et al., 2006; Thompson et al., 2005, 2006, 2009). Thompson et al. (2006) applied tasks involving executive components (e.g. the self-ordered pointing task (SOPT) and backward digit span) and visuospatial components (e.g. the visual patterns task (VPT), the Corsi Block Test (CBT), and the size just noticeable difference (Size JND) task) to investigate the role of executive resources in visuospatial working memory in patients with euthymic bipolar disorder. The patient group was impaired in the CBT, SOPT and backward digit span. Importantly, preserved VPT performance showed a strong correlation between VPT performance and executive task performance, which suggests a pattern of scaffolding structure in the impaired visual pattern task.

1.5 The structure of the healthy ageing brain

Older adults are facing both changes in psychological cognitive functions and neural-based structural changes in the brain. Age-related changes in behavioural performance are widely recognised, yet the underpinning mechanisms for behavioural outcomes are unclear until neuroimaging techniques such as fMRI and PET are available. Studies of functional neuroimaging have recently increased exponentially thus enriching our knowledge of age-related changes in neural correlates and brain structure. Although the current project does not investigate the neurobiological differences between healthy young and ageing brains, it is important to be aware of age-related neural changes. The following section will not review the entirety of the literature on age-related neurobiological changes but present two of the most noticeable neurobiological changes in the ageing brain. The relationship between these age-related neural changes and cognitive performance will also be addressed.

1.5.1 Volumetric changes

The volume of brain tissues, including grey and white matters, shrinks with age. The age-related volumetric decline in the brain structure is a result of loosening densities of synapses and it cannot be attributed to cell death. Hedden & Gabrieli (2004) reviewed literature on cognitive behaviour and neuroscience in ageing. Evidence emerged for age-related changes in the brain structure, such as lower volumes of grey matter in the brains of healthy older adults than younger adults. For example, Resnick, Pham, Kraut, Zonderman, & Davatzikos(2003) conducted a longitudinal study with MRI for 92 healthy older participants (age range 59-85). The imaging results showed gradual volumetric decline in grey and white matter in the non-pathological ageing brain. Moreover, a trend of greater white matter loss than grey matter loss was observed. While grey matter loss was most pronounced in several brain regions, such as orbital and inferior frontal, cingulate, insular, and inferior parietal, white matter loss was widespread. It is suggested that slower rates of age-related changes in brain regions may be associated with intact cognitive ability in healthy older adults.

Coffey and colleagues (2001) conducted a cross-sectional study to investigate the relationship between age-related volumetric decline and cognitive performance. The volumes of brain tissue and cerebro-spinal fluid in 320 healthy older participants were measured and associated the results with participants' neuropsychological performance. The result showed that age-specific decrease in cerebral size was associated with poor performance on attention and executive functions. Nevertheless, such brain-behaviour association was not observed in other cognitive domains, such as verbal or visuospatial ability. Age-related hippocampal volume loss is suggested to associate with episodic memory impairment in older adults (Hedden & Gabrieli, 2004). However, a recent review indicated that the relationship between volumetric decline and poor cognitive performance in ageing may be overestimated (Van Petten, 2004). A meta-analysis of thirty-three studies, which examined memory performance and hippocampal volumes in healthy participants, was performed. The results showed a strong negative correlation between hippocampal volume and episodic memory in younger adults. However, the relationship between the declined hippocampal volume and memory performance in older adults was surprisingly weak. Van Petten suggests that the relationship between hippocampal volumes and memory performance becomes extremely variable in ageing. There is general agreement that age-related cerebral volumetric decline is associated with poor performance in some cognitive domains, such as attention and executive functions. Nevertheless, the brain-behaviour association in other cognitive domains remains unclear.

1.5.2 White matter integrity

In addition to volumetric shrinkage in the ageing brain, white matter integrity is affected by age. Diffusion tensor imaging (DTI) utilises magnetic resonance technology to measure the direction and magnitude of water diffusion through cellular tissues in vivo, which was not previously possible with conventional MRI. While image intensity from standard structural MRI measures may change due to underlying compositional changes to tissues and/or the volumes of structures that are calculated, DTI observes interconnected neural networks by measuring the amount, fractional anisotropy and direction of water diffusion in tissues (Davis, Kragel, Madden, & Cabeza, 2012; Dennis & Cabeza, 2008; Madden, Bennett, & Song, 2009). DTI has been widely applied to investigate age-related white matter loss in ageing studies due to its sensitivity to changes in white matter microstructure in the brain.

Healthy older adults exhibit greater tract intensity but decreased integrity in white matter (Davis et al., 2012; Giorgio et al., 2010; Madden et al., 2009). Reduced white matter integrity is suggested to be associated with interhemispheric connectivity in the ageing brain. Davis and colleagues (2012) utilised a lateralised word matching task to explore cross-hemispheric communication between young and older adults. Cross-hemispheric communication was measured behaviourally and at the neural level; DTI measures of white matter integrity in the corpus callosum and fMRI were applied to investigate structural and functional connectivity between contralateral prefrontal cortex. The behavioural results showed that older adults benefit by distributing processing across the hemispheres as they performed better (i.e. more accurate) on bilateral than unilateral trials in the word matching task, compared to young adults. Neuroimaging evidence showed that older adults exhibited greater functional connectivity between contralateral PFC in trials that required bilateral activity supporting the behavioural results. Importantly, both behavioural and neural measures of cross-hemispheric communication were significantly correlated with DTI measures of callosal integrity, but only in older adults. The finding suggests that older adults rely heavily on bilateral pathways during cognitive processing and thus reduced white matter integrity will limit their performance. However, as young adults do not rely so much on utilising both hemispheres in processing the cognitive task, interhemispheric connectivity of white matter integrity is of no consequence to their performance.

Giorgio and colleagues (2010) assessed a number of measures of brain structure in both white matter and grey matter and found that DTI-based measures were better than conventional T1-weighted imaging in detecting widespread age-related decline in white matter microstructure. Madden and colleagues reviewed DTI studies which measure cerebral white matter integrity and their relationship with cognitive performance (Madden et al., 2009). The results suggest that reduced white matter integrity contributes to a disconnection among distributed neural systems and it is a fundamental mechanism of age-related variability in cognitive performance. Moreover, the anterior-posterior gradient of the declining white matter integrity in ageing affects information processing speed and executive functioning in ageing. The decreased white matter integrity results in disconnection among neural networks and has been associated with age-related impairments in healthy older adults. Voineskos et al. (2012) utilised DTI tractography to observe white matter tract integrity and its relationship with cognitive performance, which was derived from a neuropsychological battery. The old adult group revealed a reduced in white matter integrity which was associated with age-related cognitive decline. The findings suggest that reduced white matter integrity can account for age-related decline in healthy ageing.

1.6 Scope and aims of the project

This chapter reviews literature on age-related decline in various cognitive domains (Section1.2) with a particular focus on the visuo-spatial domain (Section 1.3). Three ageing theories are presented to understand the relationship between age-related behavioural changes and structural changes in the brain (Section 1.4). Finally, age-related alterations of the brain structure are discussed (Section 1.5).

Most neuroimaging evidence for cognitive scaffolding derives from studies with verbal related cognitive tasks in ageing literature (Cabeza et al., 2004, 2002). However, there is no evidence of scaffolding mechanisms from the visuo-spatial domain. As patient studies have displayed a pattern of ‘cognitive scaffolding’ for those with visuo-spatial impairments (as reviewed in section 1.3), the current project aims to contribute knowledge of preservation mechanisms in the ageing brain by using visuo-spatial tasks. With abundant studies which demonstrate hemispheric specialization for categorical and coordinate spatial relations (Jager & Postma, 2003; Kosslyn & Chabris, 1992; Kosslyn et al., 1989; van der Ham et al., 2009, 2007), the present project will utilise the characteristic of lateralisation of the distinct spatial relations to investigate preservation mechanisms in healthy ageing. Preservation mechanisms in older adults could be either utilising bilateral activations (in line with Cabeza et al.'s finding [2002]) or recruiting additional cognitive resources, e.g. verbal or attentional resources (in line with Park & Reuter-lorenz's view [2009]) during the hemispheric specialised visuo-spatial processing. It is hypothesised that older adults who are facing age-related cognitive decline would utilise preservation mechanisms in order to maintain declined cognitive abilities. Older adults who do not or fail to adopt sufficient preservation mechanisms would demonstrate poorer cognitive performance when performing cognitive tasks, compared with those who adopt successful cognitive scaffold strategies.

There are four main goals for the project (specific hypotheses are stated in each chapter):

To further our understanding of categorical and coordinate spatial representations in VSSTM using the proposed visuo-spatial tasks. fMRI will be adopted to observe underpinning neural mechanisms when processing the two spatial representations with the proposed tasks.

To observe age effects on categorical and coordinate spatial representations.

To explore neuropsychological functioning between higher- and lower-performance people in old age.

To explore the compensation network of the HAROLD model with visuo-spatial tasks by comparing neural correlates of young, old high-, and old low-performance participants.

Chapter 2. Development of the CATCOORD task

2.1 Introduction

Categorical and coordinate spatial representations describe two different types of spatial relations; the former explains objects' spatial relations in an abstract manner while the latter indicates objects' spatial relations in a numerically precise method (Kessels et al., 2002; Kosslyn et al., 1989). Not only do the two representations illustrate spatial relations differently, the two hemispheres show differences in the speed with which the two spatial representations are/can be processed. Kosslyn and colleagues conducted a series of studies to illustrate the hemispheric specialisation for the two spatial representations by presenting amorphous outline figures with a large dot on different visual fields. Participants were asked to judge whether the dot was on/off the figures (categorical judgment) or near/far from the figures (coordinate judgment). Findings showed that participants responded faster for categorical trials if stimuli were presented to the right visual field/left hemisphere. On the other hand, coordinate spatial judgments were responded to faster when stimuli were presented to the left visual field/right hemisphere (Kosslyn, 1987; Kosslyn et al., 1989). Visual-spatial paradigms with different stimuli have also demonstrated lateralisation effects for the two spatial representations, such as a dot and a bar, where participants are asked to judge how far the dot is away from the bar, i.e. coordinate spatial relations, or whether the dot is above/below the bar, i.e. categorical spatial relations (Borst & Kosslyn, 2010; Bruyer et al., 1997; Park, Polk, Hebrank, & Jenkins, 2010; van der Lubbe et al., 2006; Wilkinson & Donnelly, 1999); a dot and a 'blob' (Kosslyn, 1987; Kosslyn et al., 1989; Slotnick & Moo, 2006); or a dot and a cross (van der Ham & Postma, 2010; van der Ham et al., 2007). However, these tasks share a common experimental design: stimuli are presented either in the right or left visual field. That is to say, the hemispheric lateralisation effect is only revealed in experimental paradigms that present stimuli in the left or right visual field.

van der Ham and colleagues examined other factors which may distinguish the categorical and coordinate spatial representations and suggested that the inter stimulus interval (ISI) would also influence performance for categorical and coordinate judgments (van der Ham et al., 2007). A dot-cross task was utilised in their study with three different ISIs: 500ms, 2000ms, and 5000ms. The results demonstrated the hemispheric lateralisation effect for categorical and coordinate spatial representations and, more importantly, that the coordinate advantage in right hemisphere was found in the shortest maintenance time, while the categorical advantage in left hemisphere was observed when maintenance intervals were longer. The coordinate advantage in right hemisphere was deemed to be time-sensitive since it only occurred in the shortest maintenance interval. The researchers further speculated that the coordinate advantage in VSSTM emerges when verbal information is limited. This forces participants to rely on non-verbal/visual-spatial information during a short retention interval. On the other hand, the categorical advantage in the left hemisphere only emerged during longer time intervals and this is thought to be due to the recruitment of verbal strategies.

While the majority of tasks address the laterality of the two spatial representations by presenting stimuli to the left or right visual field, Dent adopted a whole visual-field task with a series of manipulations to examine verbal contribution to categorical spatial representation (Dent, 2009). The results showed a consistent categorical advantage effect, i.e. categorical spatial changed trials showed better performance than coordinate changed trials, even when verbal interference was applied. This finding suggests that categorical spatial representations are an intrinsic property of visual-spatial configurations and cannot be simply associated with verbal coding. However, a markedly long retention interval (2000ms) was utilised which may have biased the results in favour of the categorical advantage effect.

This chapter consists of two experiments to explore categorical and coordinate spatial representations in a whole visual-field task, the CATCOORD task. Experiment 1 includes three sub-experiments to observe impact of time course, verbal interference and visual-spatial perception on categorical and coordinate spatial relations; Experiment 2 utilises fMRI to observe brain activity when processing categorical or coordinate spatial relations.

2.2 Experiment 1a: CATCOORD task with unicolour, without interference

2.2.1 Introduction

This experiment is designed to examine whether the effect of time course on categorical and coordinate spatial representations could be replicated with a whole visual-field task, the CATCOORD task. Since the advantage of coordinate spatial representation in VSSTM only occurs when verbal information is unavailable to participants (van der Ham et al., 2007), the current study applies the CATCOORD task to examine whether short time courses would also benefit coordinate spatial representation when stimuli are presented at the centre of the screen and when spatial judgment cues are not provided. The present experimental paradigm explores categorical and coordinate performance when pure spatial information is provided in VSSTM.

The task follows the design of the paradigm in Dent's study with several manipulations: encoding and retention times are manipulated, while shift distances (between the reference and the target) are set at three different magnitudes. These manipulations are designed to observe whether the characteristic of time sensitivity for coordinate spatial representation exists at an early stage, e.g. during encoding, or whether it appears later when participants are unable to obtain verbal information during a short retention interval. The three magnitudes of shift size are designed to investigate 1) a possible boundary for coordinate spatial relations and 2) whether coordinate spatial representation is more pronounced if the distance between target and reference items is too subtle for verbal description to assist memory strategy in VSSTM. It is thought that participants may rely on iconic/coordinate related information that cannot be verbally described, when verbal/categorical related information is minimised. As soon as a boundary for coordinate spatial changes is crossed and accessibility for categorical representations is minimised, e.g. short encoding/retention time, coordinate performance may be elevated and results in a similar performance with categorical changes. In addition, identical stimuli features were utilised in the current task to eliminate any possible verbal assistance for the spatial judgements.

The purpose of Experiment 1a is to explore other parameters of spatial representations which were not addressed in Dent's study. Specifically, whether time courses, during the encoding and retention stages, and shift sizes, between target and reference items, would affect the categorical advantage effect with the CATCOORD task. The hypothesis is that there is a difference between categorical and coordinate spatial relations. If categorical representations are an intrinsic property in VSSTM, the categorical advantage effect would be revealed, regardless of durations of encoding and retention or subtlety of the distance change between reference and target item. Otherwise, the categorical advantage effect may be abolished when durations of encoding and retention are limited or when verbal information is unable to assist memory performance.

2.2.2 Methods

2.2.2.1 Participants

Twelve healthy young participants (6 males and 6 females, mean age=24.7, *SD*=6.9), 12 healthy young participants (4 males and 8 females, mean age=22.4, *SD*=3.0), and another 12 healthy young participants (3 males and 9 females, mean age=24.3, *SD*=5.8) were allocated to the encoding time 250ms, 500ms, and 2500ms conditions by the researcher, respectively. Although the sexes of participants were not balanced, previous studies in our lab suggested that there is no sex difference while executing the experiment task (Gallagher et al. 2012, unpublished data). The majority of participants were Newcastle University students while a very small number were employees of either the university or a company. All received a participation fee of £10 after they had completed the study. Participants were all right-handed and had normal or corrected-to-normal vision. A consent form was provided before the experiment started. The research was approved by the Faculty of Medical Sciences Ethics Committee in Newcastle University.

2.2.2.2 Stimuli

The encoding and the response image consisted of four small squares of the same colour (red) on a computer screen. The four squares were allocated to four quadrants (top-left, top-right, bottom-left, and bottom-right) and two of them would be assigned as “reference” and “target” items. Only one type of spatial relation was manipulated between reference and target whilst the other squares remained at the same positions. The target was allocated to each quadrant equally often with the reference item assigned to one of the other possible locations. The position of the target could be moved away from the reference item in three different shift sizes (15mm, 20mm, and 25mm), either vertically or horizontally.

On categorical-change trials, the spatial relation of the target and the reference locations was changed categorically (e.g. from left to right or from up to down) while its categorical spatial relations with the other two squares remained the same. On the other hand, on the coordinate-change trials only the distance between the target and the reference item was manipulated. For example, the target could be moved 15mm, 20mm, or 25mm to the right of the reference only if the target was originally placed on the right of the reference on the encoding image. Meanwhile, the spatial relations between the target and the other two squares remained the same. Figure 2-1 illustrates examples of categorical change, coordinate change and the same trials.

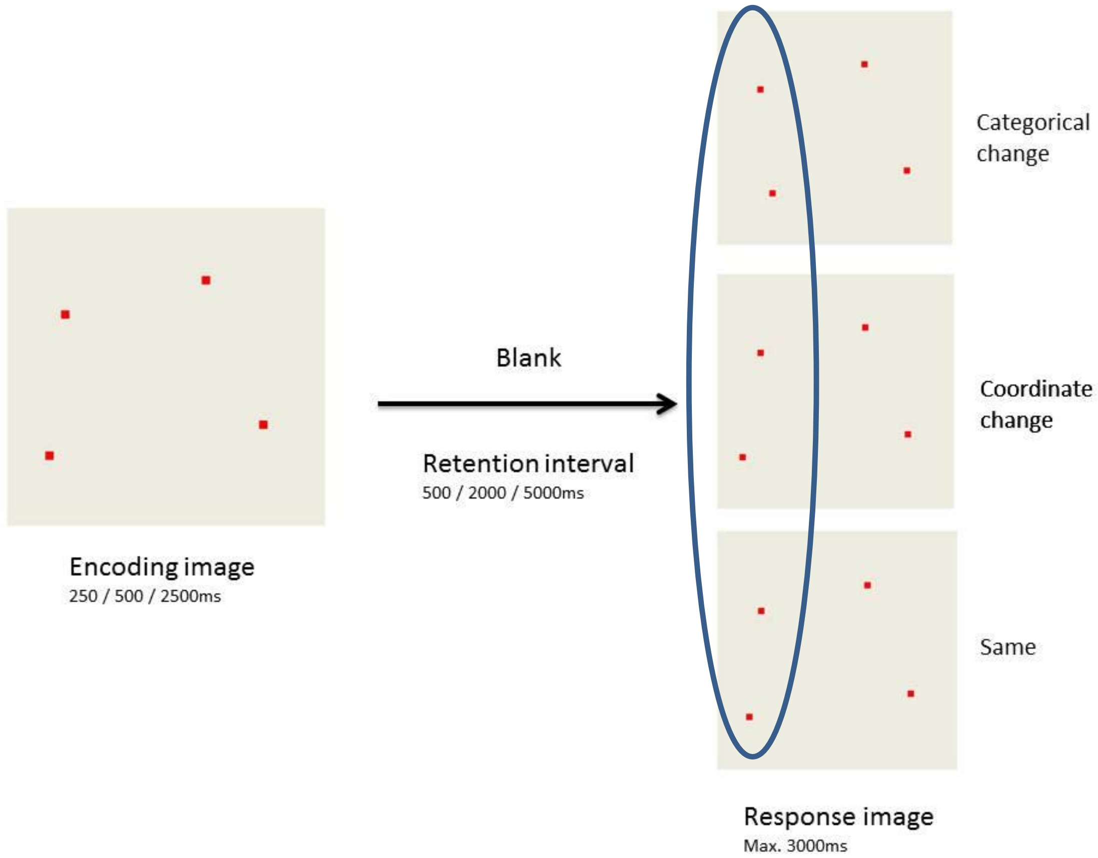


Figure 2-1. Example stimuli and a trial procedure for CATCOORD task. The oval indicates the locations of the reference (i.e. the top-left square) and the target (i.e. the bottom-left square). For the categorical change in this example, the target has moved from the left (in the encoding image) to the right of the reference. The coordinate change presents a difference in distance between the reference and the target yet the target remains on the left. The same shows no changes between the encoding image and the response image. The encoding image is the to-be-remembered image with different durations (250ms, 500ms, and 2500ms). Each participant only experienced one of the encoding times and the three different retention intervals (500ms, 2000ms, and 5000ms).

2.2.2.3 Design

The study was a mixed design as each participant experienced the three retention intervals (500ms, 2000ms, and 5000ms) along with one of the encoding times (250ms, 500ms, 2000ms). In order to avoid any possible confounding caused by fatigue, participants were separated into three groups in accordance with encoding times in a between-subjects design. There were 12 categorical-change trials (4 trials for each of the three shifts), 12 coordinate-change trials (each shift containing 4 trials), and 12 same trials in one block. In the same trials, the four squares remained at the same positions in both encoding and response images. Participants went through three blocks with each retention interval and each of the 36 trials was randomised within a block. Overall, each participant performed nine blocks, three for each retention interval. A short break was provided between blocks. In order to minimise possible perceptual/physical carry over effects caused by different orders of the three retention intervals, participants always performed the shortest retention interval followed by the medium retention interval, and the longest maintenance time was performed last. Depending on the encoding time that a participant was assigned, the experiment durations were from 40 minutes to 70 minutes.

2.2.2.4 Procedure

Each participant was tested individually in a quiet room. Stimuli presentation and response collection were completed using E-Prime software, (Psychology Software Tools, Inc., Sharpsburg, PA). During the practice session, participants experienced 6 practice trials with feedback to ensure that they understood the experiment procedure and the instructions. Participants then completed the formal experiment session. An experimental trial began with a blank screen (500ms) and then a fixation point “+” at the centre of the computer screen for another 500ms. The encoding image was then shown for either 250ms, 500ms, or 2500ms, followed by a blank retention interval for either 500ms, 2000ms, or 5000ms. The response image was then displayed. Participants were asked to make a same/different judgment of the two successive images during the display of the response image (maximum 3000ms) (see Figure 2-1 for an illustration). Participants were instructed to use their left or right index fingers to press the key “z” or “m” on the keyboard; the assignment of key to response was counterbalanced over participants. The next trial started as soon as participants made a response. Both accuracy and reaction times were recorded using E-Prime software.

2.2.2.5 Data analysis

Two types of analysis were included. The first analysis addressed the effects of the three experimental conditions: categorical, coordinate and same spatial relations, and whether the manipulation of retention interval and encoding time would influence performance on these spatial judgments. A 3 (condition: categorical vs. coordinate vs. same condition) × 3 (retention interval: 500ms vs. 2000 vs. 5000ms) within-subject repeated measures combined with a between-subject variable (encoding time: 250ms vs. 500ms vs. 2500ms) analysis of variance (ANOVA) was performed. The results focus on interactions between condition and retention interval, condition and encoding time, and main effects of condition, retention interval, and encoding time.

The second analysis aimed to observe whether manipulations of shift size, retention interval, and encoding time would influence performance for the two spatial relations. A 2 (spatial relation: categorical vs. coordinate relation) × 3 (retention interval: 500ms vs. 2000ms vs. 5000ms) × 3 (shift size: 15mm vs. 20mm vs. 25mm) within-subject repeated measures combined with a between-subject variable (encoding time: 250ms vs. 500ms vs. 2500ms) ANOVA was performed. Note that the same condition was excluded in this analysis since there were no spatial shifts for objects in the same trials. The results will report the interaction between spatial relation and shift size. Interactions between spatial relation and retention interval, and spatial relation and encoding time will be mentioned only briefly since they would have been reported in the first analysis. Moreover, main effects of spatial relation, shift size, retention interval, and encoding time will be reported.

The results of other interactions in the first and second analysis will be shown in the Appendix.

2.2.3 Results

Figure 2-2 shows the results of mean accuracy of categorical, coordinate, and the same condition in different encoding times and retention intervals from the first analysis. Accuracy of performance showed no significant interactions between condition and encoding time ($F(4,66)=1.59$, $p=0.188$) and condition and retention interval ($F<1$). Neither encoding time nor retention interval affected spatial judgments. Main effects of condition and retention interval were found to be significant ($F(2,66)=10.49$ and $F(2,66)=30.15$, respectively, $ps<0.001$). Post hoc analysis showed that the coordinate condition (68.4%) was performed significantly worse than the categorical (76.3%) ($t(35)=-5.96$, $p<0.001$) and the same condition (79.5%) ($t(35)=-3.75$, $p=0.001$) but the difference between the categorical and same condition was not significant. The main effect of retention interval suggested that shorter retention intervals receive better memory performance; the 500ms retention interval showed the best performance at 78.6%, followed by the 2000ms retention interval

(76.1%), and the 5000ms retention interval was memorised the worst (69.8%) (*p*s<0.05). The between-subject variable, encoding time, did not affect memory performance (*F*<1).

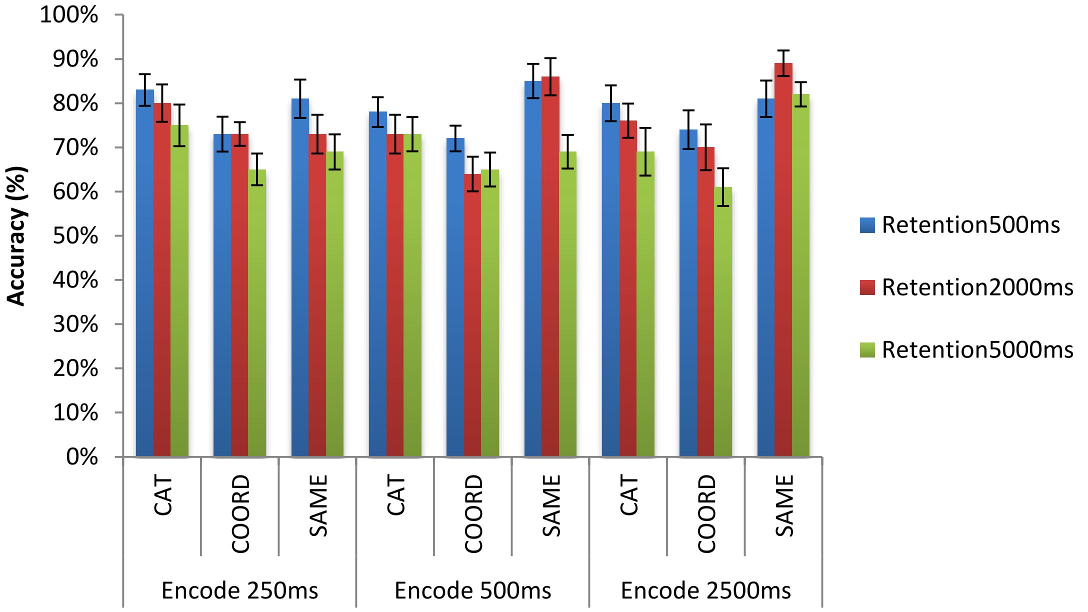


Figure 2-2. Mean accuracy of the categorical, coordinate, and same trials with the three encoding times (250ms, 500ms, and 2500ms) and the three retention intervals (500ms, 2000ms, and 5000ms).

Figure 2-3 shows the results of reaction times from the first analysis. There were no significant interactions between condition and encoding time, and condition and retention interval (*F*s<1). The duration of encoding times and retention intervals did not influence participants' response times on the three conditions. A main effect of spatial relation was not significant, suggesting that categorical-change trials, coordinate-change trials, and the same trials received similar response times (F(2,66)=1.68, *p*=0.194). A significant effect of retention interval was found (*F*(2,66)=47.58, *p*<0.001); short retention intervals resulted in faster reaction times. Post hoc analysis showed that the shortest retention interval resulted in the quickest responses (957ms), followed by the medium retention interval (1068ms), and the longest retention interval was responded to the slowest by participants (1208ms) (*p*s<0.001). There was no significant difference between the three encoding groups (*F*(2,33)=2.22, *p*=0.125).

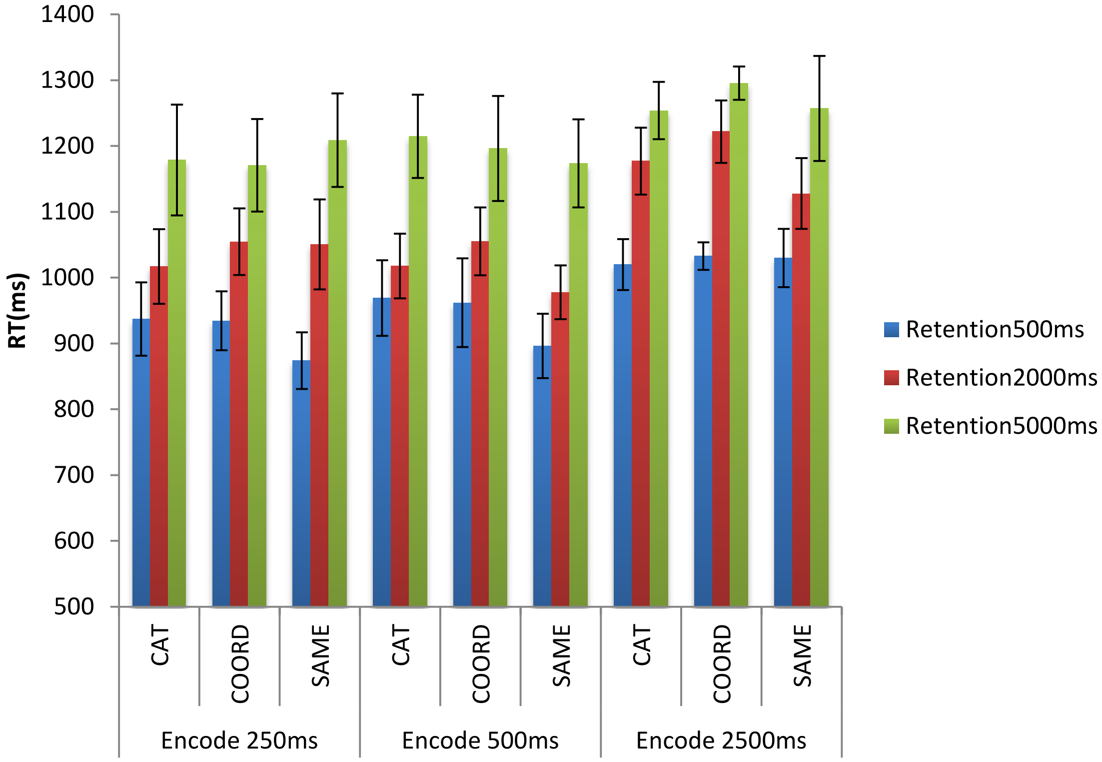


Figure 2-3. Mean reaction times of the categorical, coordinate, and the same trial with the three encoding times (250ms, 500ms, and 2500ms) and the three retention intervals (500ms, 2000ms, 5000ms).

The second analysis was performed to observe the impact of each manipulated variable on categorical and coordinate spatial representations. Figure 2-4 depicts the mean accuracy of categorical- and coordinate-change trials with the encoding times, retention intervals and shift sizes. Importantly, a significant interaction was found when comparing spatial relation and shift size ($F(2,66)=11.88$, $p<0.001$). Paired sample t-test demonstrated that categorical-change trials were performed better than coordinate-change trials in the 15mm and 20mm shift sizes ($t(35)=6.10$ and $t(35)=4.30$, respectively, $ps<0.001$), but with the 25mm shift the difference only reached trend level ($t(35)=1.76$, $p=0.088$). The interaction indicated that even with the smallest shift distance, participants were still able to detect categorical changes better than coordinate changes. None of the other interactions between spatial relation and encoding time, spatial relation and retention interval were significant. A main effect of spatial relation was significant ($F(1,33)=36.75$, $p<0.001$). Categorical spatial relations (76.5%) were performed better than coordinate spatial relations (68.4%).

Moreover, effects of shift size and retention interval were also significant ($F(2,66)=180.41$ and $F(2, 66)=15.20$, respectively, $ps<0.001$). The post hoc analysis indicates that the largest shift (25mm) led to the best performance (85.5%), followed by the 20mm shift (73.7%), and the smallest shift size (15mm) showed the worst performance (58.2%). Greater shift sizes led to better performance, as they were easier to detect. Similar to the previous analysis, the main effect of retention interval suggests that better performance was found in shorter retention intervals. The three encoding groups did not show significant differences on memory performance ($F<1$).

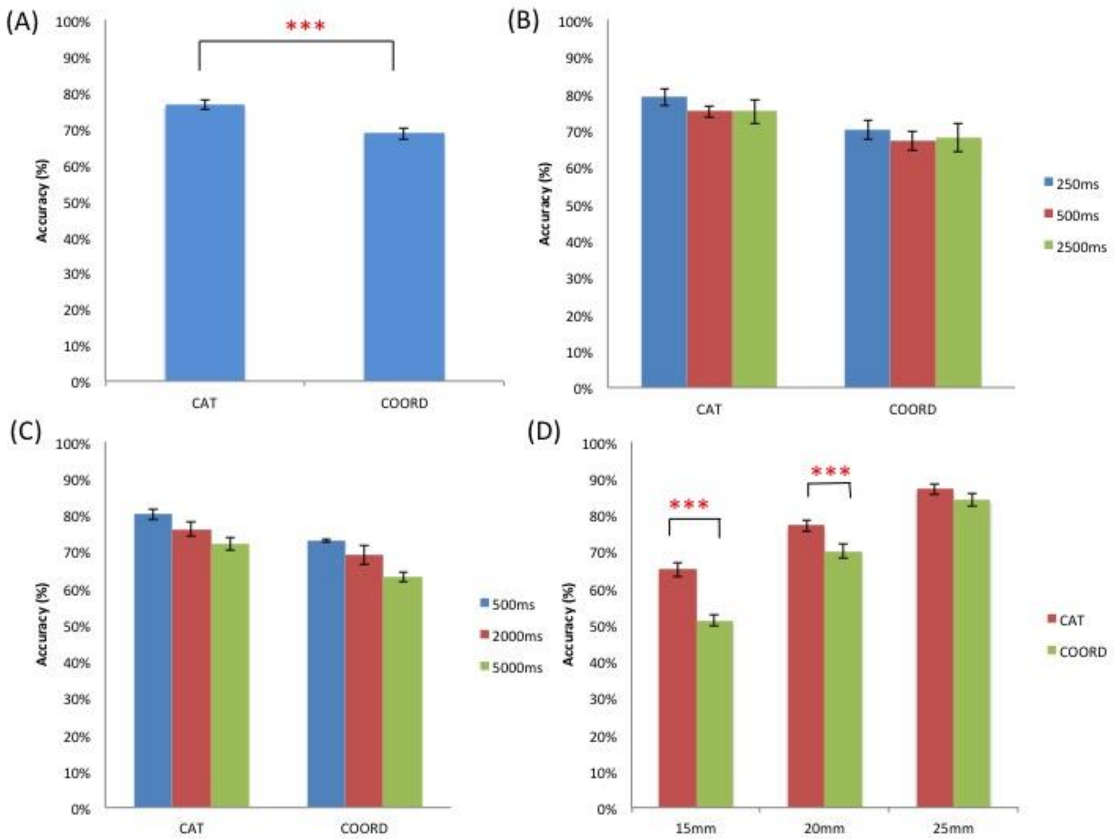


Figure 2-4. Mean accuracy of (A) categorical- and coordinate-change trials, (B) spatial relations and encoding times, (C) spatial relations and retention intervals, and (D) spatial relations and shift sizes. '***'=$p<0.001$.

Figure 2-5 shows the results for reaction times. There were no significant interactions between spatial relation and encoding time ($F(2,33)=1.21$, $p=0.310$), spatial relation and shift size ($F(2,66)=1.89$, $p=0.159$), and spatial relation and retention interval ($F(2,66)=1.92$,

$p=0.155$). None of the variables affected response times on categorical and coordinate spatial judgments. A main effect of spatial relation was not significant, suggesting that the two types of spatial relations were responded to similarly (CAT vs. COORD: 1096ms vs. 1117ms) ($F(1,33)=2.764$, $p=0.106$). Participants performed better on categorical than coordinate judgments within similar duration of response times, which indicates that the categorical spatial representations are inherent in VSSTM. At least, the categorical advantage effect is still observed within the parameters examined in the current experiment. Main effects of shift size and retention interval were significant ($F(2,66)=52.16$ and $F(2, 66)=35.44$, respectively, $ps<0.001$). Post hoc analysis indicates that larger shift sizes received shorter response times. The greatest shift size demonstrated the fastest response time (1041ms), followed by the medium shift (1088ms), and the smallest shift size received the slowest response time (1189ms) ($ps<0.005$). In addition, the main effect of retention interval shows that slower response times were found for longer retention intervals. Participants responded the fastest after the shortest retention interval (982ms), followed by the medium interval (1102ms), and the longest retention interval showed the slowest response time (1235ms). The three different encoding groups did not perform differently ($F(2,33)=2.33$, $p=0.113$).

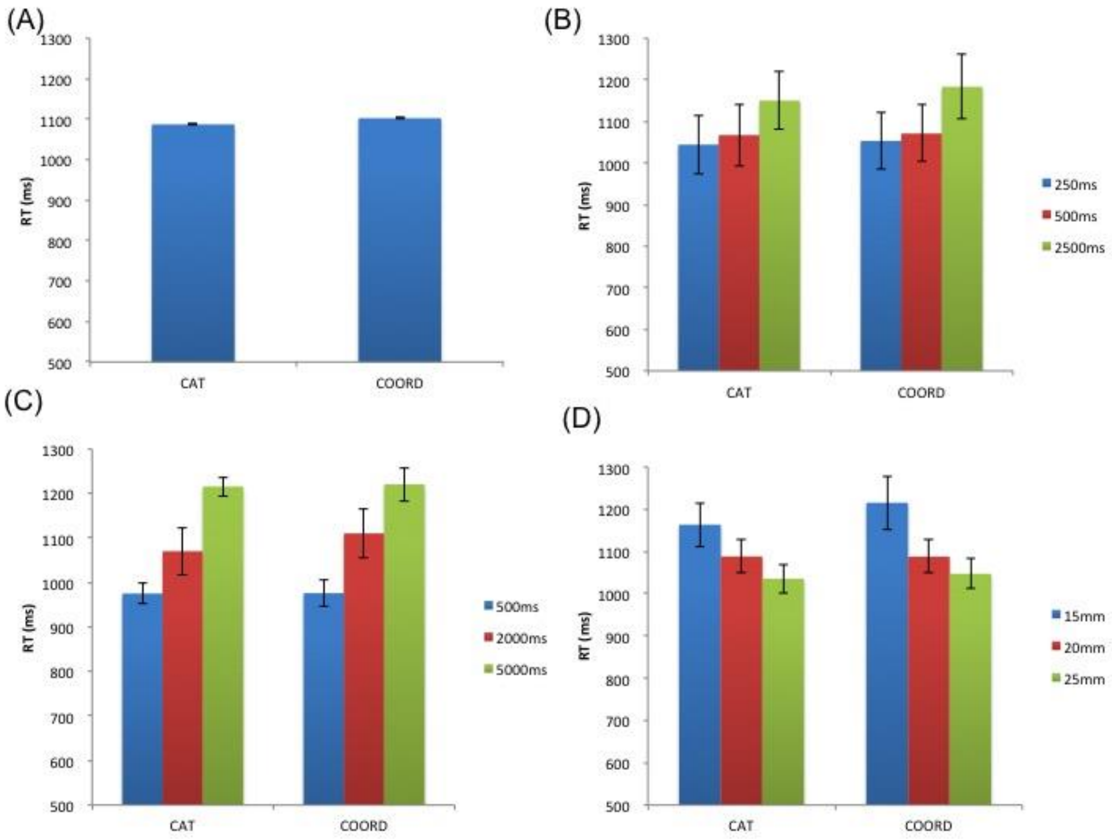


Figure 2-5. Mean reaction times of (A) categorical- and coordinate-change trials, (B) spatial relations and encoding times, (C) spatial relations and retention intervals, and (D) spatial relations and shift sizes.

2.2.4 Summary and discussion of Experiment 1a

The current results have replicated and extended Dent's findings by showing the categorical advantage effect with different parameters, manipulated using the CATCOORD task. Categorical changes result in better performance than coordinate changes, regardless of shift size or encoding time or retention interval of target. Importantly, in the shortest encoding time, where it was assumed to be difficult to encode verbal categorical information in memory and participants were putatively forced to rely on non-verbal visual-spatial information, categorical-change trials were still performed better than coordinate-change trials. In addition, when participants were assumed to rely on precise coordinate spatial representations for the smallest shift, categorical spatial changes were still easier to detect than coordinate spatial changes. In terms of retention interval, which has been demonstrated to have an influence on the two spatial representations, categorical judgments were still found to be better than coordinate judgments. Specifically, in the shortest retention interval where verbal information was thought to be minimal and coordinate spatial attributes were heavily relied on in VSSTM, the categorical advantage effect was still found. Taken together, the present study demonstrated a difference between categorical and coordinate representations in visuospatial representations, with better performance for categorical than coordinate changes consistently observed. More importantly, the findings support the notion of categorical spatial relations being an intrinsic property of encoding spatial arrays. When encoding and retention time were short and only non-verbal, visual-positional information was provided in the task, categorical spatial changes were still performed better than coordinate spatial changes.

The results replicated the previously found categorical advantage effect. Importantly, even with the manipulated encoding times, shift sizes, and retention intervals, which were designed to inhibit the formation of categorical representations, the categorical advantage effect was still found. Different from the findings of van der Ham et al. (2007), the current study did not demonstrate the sensitivity to different time courses for coordinate spatial relations. Several differences between their experiment design and the current design are illustrated in Table 2-1. The current experiment did not provide an explicit clue before spatial judgments and the stimuli were presented at the centre of the screen. These manipulations were designed to observe the two spatial representations without the characteristic of lateralisation. When participants were less likely to utilise verbal/categorical assistance to perform the task and had to heavily rely on iconic/coordinate related information, i.e. when the stimuli were presented rapidly (250ms) and retention interval was the shortest (500ms), a robust advantage of categorical over coordinate spatial relations was still found. The notion that the two spatial representations are sensitive to different time courses may only be applied when participants are explicitly instructed to make a certain spatial judgment and/or when stimuli are presented on a half visual field. Decay in memory performance associated with longer retention intervals illustrates a conventional phenomenon of many memory tasks. However, the fact that duration of encoding time did not affect participants' performance may be due to a between-subject design.

Table 2-1. Experiment design and methodology comparison between van der Ham et al. (2007) and the current experiment.

	van der Ham et al. (2007)	**Experiment 1a**
Experiment paradigm	A dot-cross task	The CATCOORD task†
Stimuli presentation	Half visual field	Whole visual field
Explicit instructions of spatial judgments	Yes	No
Encoding times	Fixed (150ms)	Different (250ms, 500ms, 2500ms) (N.B. between-subject variable)
Retention intervals	Different (500ms, 2000ms, 5000ms)	Different (500ms, 2000ms, 5000ms)
Manipulation of shift sizes	Yes (4 possible positions in each quadrant of the cross)	Yes (15mm, 20mm, 25mm)

† *As with Dent (2009)*

It is suggested that the magnitude of shifts is an important factor in coordinate spatial representations. However, Dent (2009) aimed to distinguish categorical and coordinate spatial representations have only concentrated on categorical effects while other possible manipulations that may reveal the coordinate effects in VSSTM seem to have been omitted. As the distances between target and reference in Dent's work was fixed, the current study utilised a systematic manipulation of the distances between the targets and the references in order to explore categorical boundary in VSSTM. Minimal distance changes between objects may be outside of the categorical boundary and lead the categorical advantage effect to disappear in VSSTM. Moreover, the manipulation of subtle shifts between objects may benefit coordinate representations as they are sensitive to precise spatial changes. An identical colour of stimuli was used to provide limited information of objects' identity and enhance spatial and positional features in the task. Participants may hence have had to rely on coordinate more than categorical spatial representations in trials with the smallest shift. Nevertheless, judgments on categorical spatial relations were still performed better than those on coordinate spatial relations. That is to say, the role of categorical spatial representations is dominant and coordinate spatial representations may be supplementary in VSSTM.

Verbal codes are seen as one of the attributes of categorical spatial representations. Dent (2009) conducted an experiment with an articulatory suppression task and found better performance in categorical than coordinate relations. Categorical changes were still more obvious than coordinate changes, even when one of their properties, the verbal component, was interrupted by articulatory suppression. Thus he deems that categorical representations are an immediate, intrinsic property in visuospatial representations. Moreover, van der Ham's study (2007) showed that categorical spatial relations decayed less, even in longer retention intervals (2000ms and 5000ms). They suggested that longer retention intervals might provide opportunities for participants to apply a more verbal memorisation strategy, which assisted for categorical representations. The maintenance interval (2 seconds) applied in Dent's study may have already created a bias in favour of categorical spatial representations. Before concluding that verbal information is an intrinsic property of categorical spatial representations in visual spatial configurations, further examinations on the two subunits of categorical representations in VSSTM are required.

In sum, Experiment 1a has replicated the findings by Dent (2009) and showed a consistent categorical advantage throughout various experiment parameters with the CATCOORD task. The contribution of categorical representations is salient in visuo-spatial relations even when the visual capacity is forced to extremes (e.g. 250ms presentation time of the stimuli) or in conditions where categorical information is minimal (e.g. 15mm shift of the targets).

2.3 Experiment 1b: CATCOORD task with unicolour, with/without auditory verbal interference

2.3.1 Introduction

This experiment is designed to interfere with categorical spatial representation by altering the articulatory suppression adopted by Dent (2009). While articulatory suppression is used to interfere with phonological loop and to reduce verbal coding for objects, the current experiment utilised auditory verbal interference to interfere with categorical representations. The experiment aimed to investigate whether the apparent categorical advantage effect (see in Experiment 1a) would be removed when verbal labels are targeted. Unlike Dent, who adopted articulatory suppression throughout the task, auditory verbal interference was introduced into the CATCOORD task in order to eliminate any possible influences triggered by actively producing a sound. Participants heard different ‘intervention words’ throughout the experiment: spatially relevant words (e.g. below, right) vs. spatially irrelevant words (e.g. bowl, rabbit) vs. silent condition, from the beginning of a trial to maximise the intrusion into categorical verbal processing. Passive interference was adopted in the experiment because the effect of typical verbal utterances may be too influential, which would cause poor performance for both spatial representations. Moreover, the design ensures that only categorical spatial representation will be interrupted from the beginning of the visuo-spatial process. On the other hand, coordinate representations that present spatial relations in fine-grained, metric manners, should not be influenced by any of these spatially relevant words. Introduction of spatially irrelevant words should not have an influence on either of the spatial representations. It is predicted that categorical representations would be interfered with when the spatially relevant words are played during the experiment. The effect of categorical advantage in VSSTM would be reduced or even removed.

2.3.2 Methods

2.3.2.1 Participants

Twelve right-handed healthy young participants (5 males and 7 females, mean age=23.5, *SD*=5.0) were assigned to a relevant interference group in which only spatially relevant words were applied, 12 right-handed healthy young participants (1 male and 11 females, mean age=22.8, *SD*=3.3) were assigned to an irrelevant interference group in which only spatially irrelevant words were played to participants. Another 12 right-handed healthy young participants (5 males and 7 females, mean age=24.3, *SD*=4.8) were recruited to a silent group. The majority of participants were university students while very small number were employees of either a university or a company. All received a participation fee of £10 after they had completed the study. Participants had normal or corrected-to-normal vision and provided consent. The research was approved by the Faculty of Medical Sciences Ethics Committee in Newcastle University.

2.3.2.2 Stimuli, design and procedure

The stimuli were identical to Exp.1a. The study was a mixed design as each participant experienced three encoding times (250ms, 500ms, and 2500ms) and three shift sizes (15mm, 20mm, and 25mm) along with one of the interference types. The three types of verbal interference, spatially relevant interference group, irrelevant interference group, and silent/no interference group, were applied as a between-subject design. Both spatially relevant words and irrelevant words were pre-recorded and were embedded in the E-prime script. In the spatially relevant words condition, participants heard “left”, “right”, “above”, and “below” repeatedly. The sequence of irrelevant words was “land”, “rabbit”, “acorn”, and “bowl.” Moreover, retention interval was fixed to 2000ms in the current experiment. The experimental procedure was similar to Exp.1a, with the addition of headphones for participants in order to hear the interventions.

2.3.2.3 Data analysis

Two types of analysis were carried out in a similar way to the previous experiment. A 3 (condition: categorical vs. coordinate vs. same condition) × 3 (encoding time: 250ms vs. 500 vs. 2500ms) within-subject repeated measures combined with a between-subject variable (interference type: (spatially) relevant interference vs. irrelevant interference vs. no interference) ANOVA was performed in the first analysis. The results will focus on interactions between condition and encoding time, condition and interference type, and main effects of condition, encoding time, and interference type. The second analysis was a 4-way ANOVA to investigate effects of shift size (15mm, 20mm, and 25mm), encoding time, and interference type on categorical and coordinate performance. The same condition was excluded in the second analysis since shift did not exist in the same trials. Interactions between spatial relation and shift size, spatial relation and encoding time, and spatial relation and interference type, as well as main effects of spatial relation, shift size, encode time, and interference type will be reported in the result section.

The results of other interactions in the first and second analysis will be reported in the Appendix.

2.3.3 Results

The results of mean accuracy for the three conditions and the three encoding times in the three interference groups are depicted in Figure 2-6. The interactions between condition and encoding time, and condition and interference type were non-significant (*F*s<1). Neither the encoding time nor the interference type affected performance on categorical-change, coordinate-change, or the same trials. The main effect of condition was significant ($F(2,66)=61.78$, $p<0.001$); the same condition (77.4%) was performed the best, followed by the categorical condition (67.4%), and the coordinate condition was performed the worst (47.3%) ($ps \leq 0.001$). The main effect of encoding time was also significant ($F(2,66)=10.39$, $p<0.001$). Participants showed the best performance in the 2500ms encoding time (66.8%), followed by the 500ms encoding time (64.3%), and the 250ms encoding time showed the worst performance (61.0%). Better performance on longer encoding times might be because they enabled participants to generate memory strategies. The between-subject variable, interference type, did not affect participants' memory performance ($F(2,33)=1.46$, $p=0.247$). Spatially relevant words did not affect performance on categorical over coordinate spatial judgements.

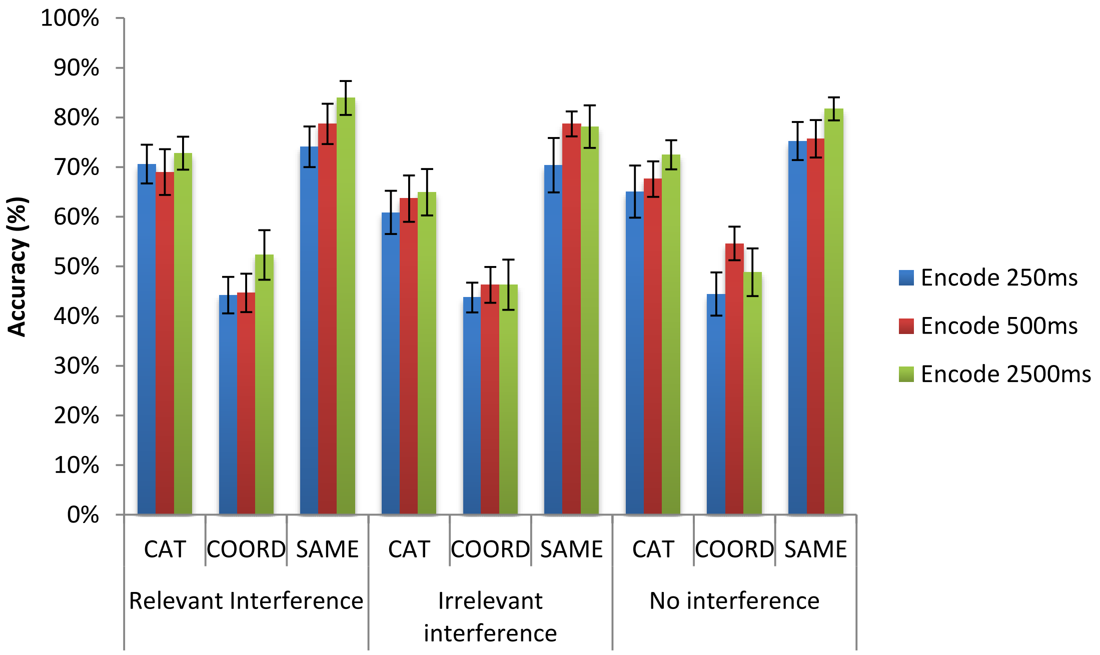


Figure 2-6. Mean accuracy of three interference types for the categorical, coordinate, and same condition with the three encoding times (250ms, 500ms, and 2500ms).

Figure 2-7 illustrates reaction times for the three interference groups with the three conditions and the three encoding times. Interactions between condition and interference type in reaction times was found to be significant ($F(4,66)=2.72$, $p=0.037$). Post hoc analysis showed that the spatially relevant interference group revealed faster responses than the no interference group on all three conditions: the categorical condition ($t(22)=-2.08$, $p=0.049$), the coordinate condition ($t(22)=-2.35$, $p=0.028$) and the same condition ($t(22)=-3.34$, $p=0.003$). However, there was no significant difference between the categorical vs. the coordinate condition, and the coordinate vs. the same condition. The interaction between condition and encoding time was not significant ($F(4,132)=1.30$, $p=0.273$), suggesting that response speed of spatial judgments was not influenced by the duration of stimuli presentation. Main effects of condition and encoding time were significant ($F(2,66)=7.92$ and $F(2,66)=19.14$, respectively, $ps \leq 0.001$). Participants responded most quickly for the same trials (1053ms) whereas the difference between categorical-change trials (1089ms) and coordinate-change trials (1093ms) was not significant. The main effect of encoding time indicated that the longest encoding time received significantly slower responses (1184ms) than the medium encoding time (1006ms) and the shortest encoding time (1045ms) ($ps<0.001$). Reaction times between the shortest and the medium encoding time did not differ significantly. Importantly, the main effect of interference type was significant ($F(2,33)=3.71$, $p=0.035$). Post hoc analysis indicated that the relevant interference group showed faster responses than the no interference group (1015ms vs. 1182ms, $t(11)=-2.61$, $p=0.024$) yet the irrelevant interference group did not perform differently from the no interference group (1039ms vs. 1182ms, $t(11)=-1.95$, $p=0.077$). Moreover, difference in response speed between the relevant and irrelevant interference group was not significant ($t(11)=-0.35$, $p=0.731$).

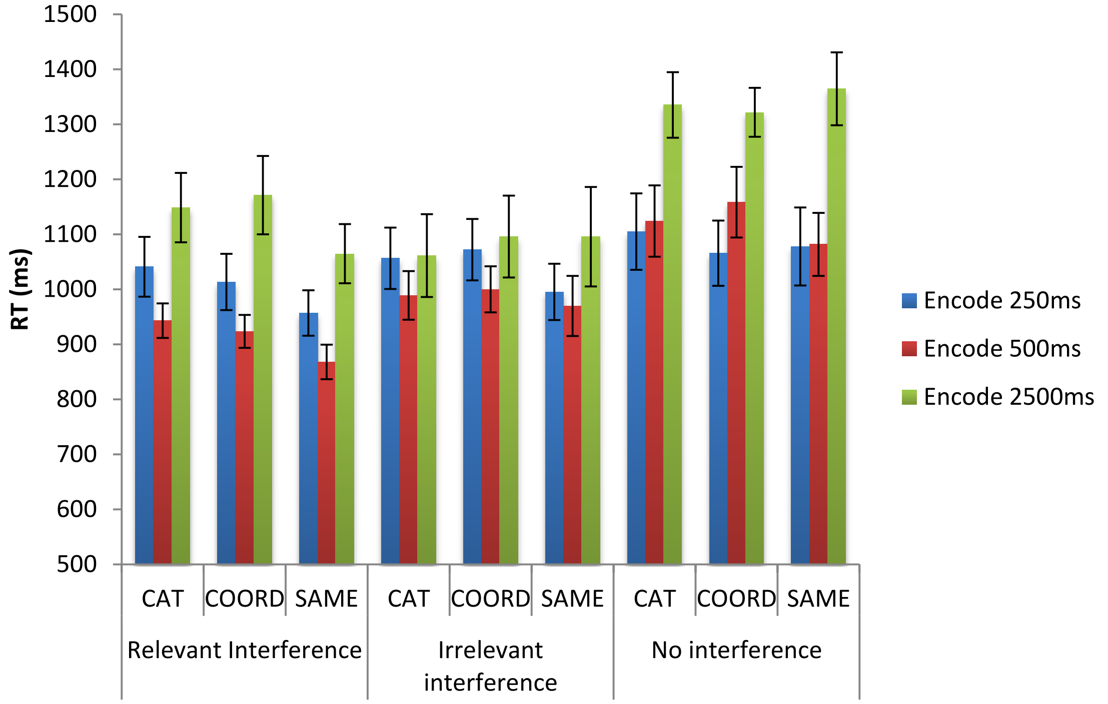


Figure 2-7. Mean reaction times of three interference types for the categorical, coordinate and the same condition with the three encoding times (250ms, 500ms, and 2500ms).

The second analysis examines the effects of each manipulated variable, encoding time, shift size, and interference type, on categorical and coordinate spatial judgments. Figure 2-8 illustrates the mean accuracy of categorical and coordinate spatial judgments with different interference types, encoding times, and shift sizes. There was a significant interaction between spatial relation and shift size ($F(2,66)=39.356$, $p<0.001$). Post hoc analysis indicated that categorical-change trials were always memorised better than coordinate-change trials regardless of shift sizes (*p*s<0.001). Even in the smallest shift size, where verbal labels were unlikely to be formed, the categorical condition (61.7%) was still performed significantly better than the coordinate condition (31.8%) ($t(35)=12.06$, $p<0.001$). However, the interactions between spatial relation and interference type, and spatial relation and encoding time were not significant ($F(2,33)=1.05$, $p=0.362$ and $F<1$, respectively). Neither interference type nor encoding time affected categorical and coordinate spatial memory performance. The main effect of spatial relation was significant ($F(1,33)=128.36$, $p<0.001$). The categorical advantage was demonstrated by better performance in categorical-change trials (67.4%) than coordinate-change trials (47.3%). The main effects of shift size and encoding time were also significant ($F(2,66)=104.78$, $p<0.001$ and $F(2,66)=3.16$, $p=0.049$, respectively). Post hoc analysis indicated that trials with bigger shift sizes were performed better. The largest shift size received the best performance (68.4%), followed by the medium shift size (56.9%), and the smallest shift size was hard to detect thus resulted in the worst memory performance (46.7%). The significant effect of encoding time was derived from the difference between the performance in the longest encoding time (59.6%) and the shortest encoding time (54.8%). The interference type did not affect spatial judgments (F<1). Spatially relevant words did not affect memory performance on categorical spatial judgments more than coordinate spatial judgments.

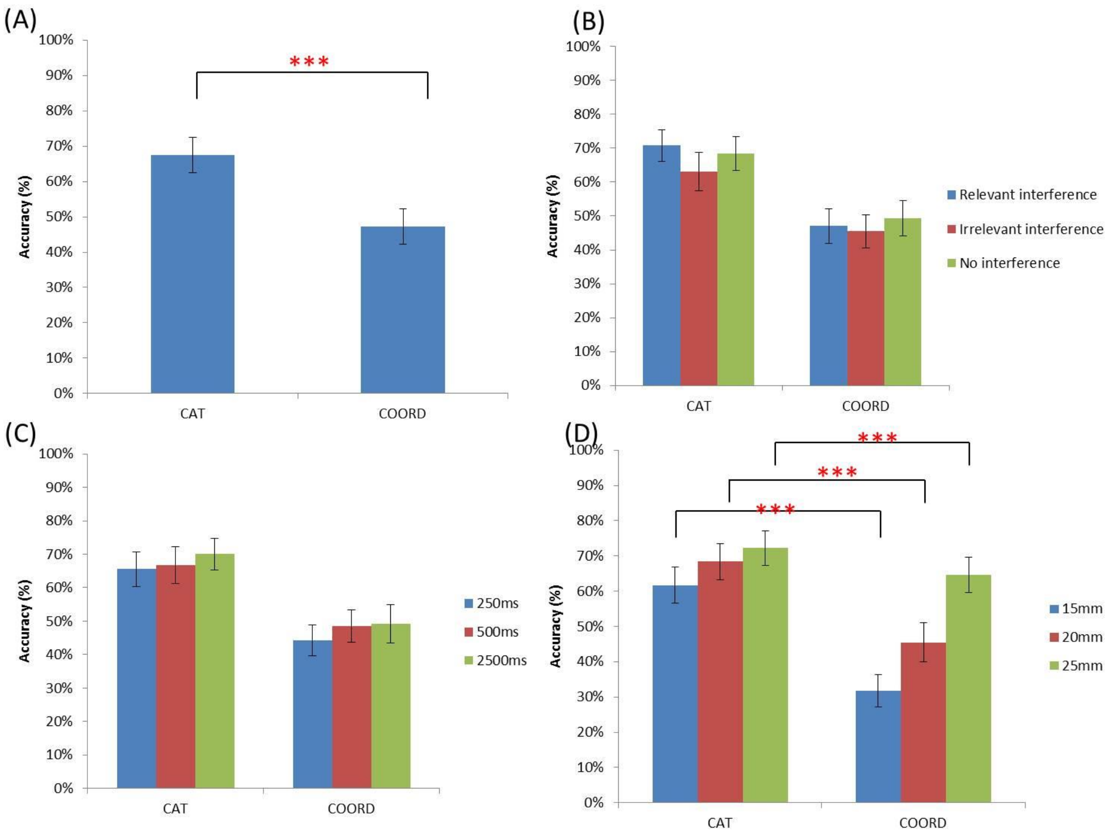


Figure 2-8. Mean accuracy of (A) categorical- and coordinate-change trials, (B) spatial relations vs. types of interference group, (C) spatial relations and encoding times, and (D) spatial relations and shift sizes. '***'=p <0.001.

Mean reaction times are depicted in Figure 2-9. The categorical and coordinate spatial judgments showed similar response times for different encoding times ($F(2,66)=1.31$, $p=0.227$), shift sizes, or interference types (Fs<1). The main effect of encoding time was significant ($F(2,66)=15.72$, $p<0.001$). The 2500ms encoding time (1189ms) was performed significantly slower than the 500ms (1023ms) and the 250ms (1059ms) ($ps \leq 0.001$). However, there was no main effect for spatial relation ($F<1$) and shift size ($F(2,66)=01.58$, $p=0.214$). The main effect of interference type was not significant ($F(2,33)=3.09$, $p=0.059$). The type of interference did not affect response speed for spatial judgments.

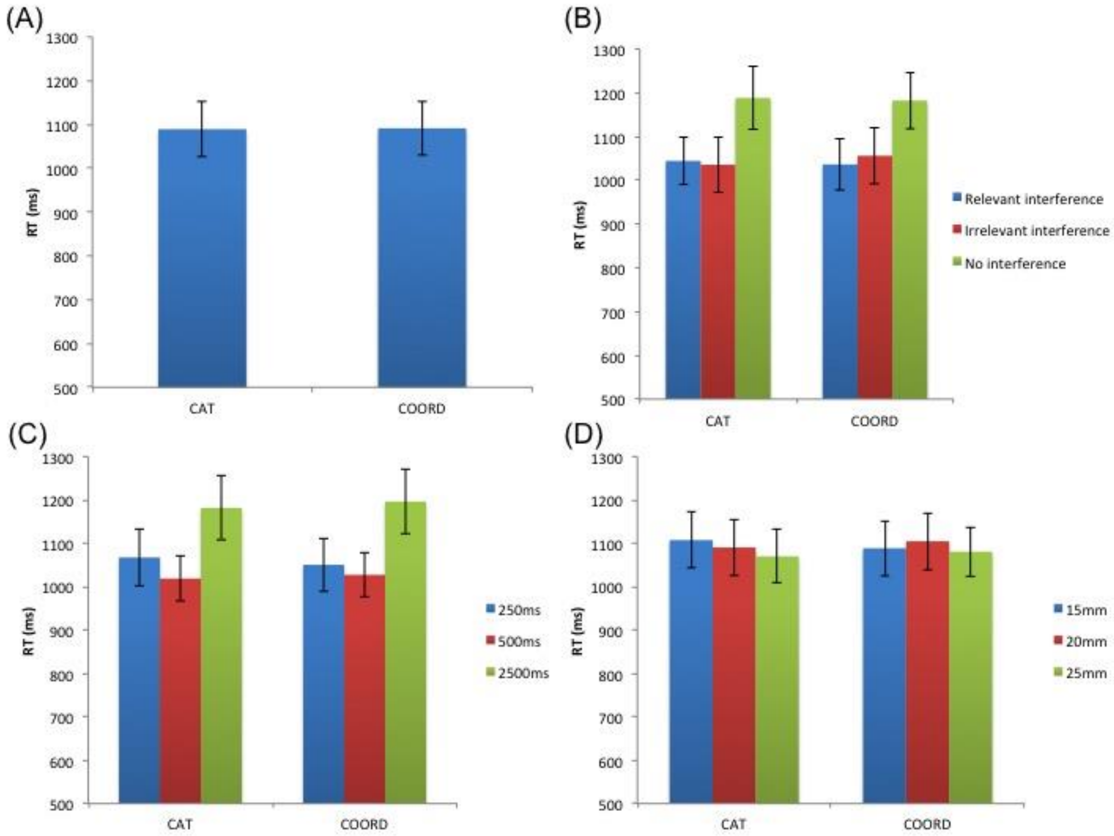


Figure 2-9. Mean RT of (A) categorical- and coordinate-change trials, (B) spatial relations vs. types of interference group, (C) spatial relations and encoding times, and (D) spatial relations and shift sizes.

To summarise the results from the above two analyses, interaction between spatial relation and interference type was not found. The types of interference did not influence performance for categorical and coordinate spatial judgments. Importantly, the categorical advantage effect was observed even when the spatially relevant words were played to participants. Encoding time was designed as a within-subject variable in this experiment and its effect on VSSTM has been found. Participants performed better when the presentation of stimuli was longer.

2.3.4 Summary and discussion of Experiment 1b

The most important manipulation for the current experiment was a manipulation of interference. Since a consistent categorical advantage effect was found in Exp.1a, introducing spatially relevant word interferences could intrude on the encoding of categorical spatial relations in VSSTM. However, the current study showed that a robust categorical advantage effect was demonstrated even when spatially relevant words were applied throughout visual-spatial processing. More importantly, even in the shortest encoding time and the smallest shift size with spatially relevant words interference, where verbal information was hard to achieve, categorical- change trials (62.5%) were still performed better than coordinate-change trials (29.2%).

Articulatory suppression was adopted in the previous study in order to disrupt verbal encoding in working memory capacity, but the results still found better categorical than coordinate performance (Dent, 2009). In addition, van der Ham & Borst (2011) applied two types of interference task with a dot-bar half visual-field task and found out that only spatial tapping interference, not articulatory suppression, affected categorical and coordinate performance. The present experiment introduced auditory verbal intervention by playing spatially relevant words. Categorical representations can be interrupted more precisely by the concepts of these words. Yet the categorical advantage effect was still found. Compared to spatial tapping, the effect of auditory verbal interference may be less effective in disrupting spatial representations.

An interesting result occurred in the current experiment: participants showed slower response times in the no interference condition than the spatially relevant interference condition, while their accuracy performances were similar. Auditory verbal intervention was designed to interrupt verbal labels for categorical representations. However, it seems that it triggered participants to adopt a visual-spatial related memory strategy instead. The performance for both spatial relations was improved, as faster responses were observed only when spatially relevant words were played to participants throughout the experiment. Participants may have encoded the visual-spatial array in a different way when visual-spatial judgments were not explicitly provided. When interference of any sort was given, it perhaps cued participants to utilise spatial/perceptual codes and resulted in “better” performance. Inconsistent findings were found with different types of interference; articulatory suppression (conducted by Dent, 2009) served interference purposes by showing poorer accuracy performance on both spatial representations. Auditory verbal intervention in the current experiment, however, seemed to ‘benefit’ cognitive performance by speeding up its response times. Future studies could address roles of interference effect by adopting types of interference.

Although previous literature usually addresses the two types of spatial relations in VSSTM, Postma and colleagues further suggested that there are two subcomponents in categorical representations: categorical-verbal codes and categorical-perceptual codes (Postma, Kessels, van Asselen, & Asselen, 2008). While categorical-verbal codes consist of verbal elements in categorical representations, categorical-perceptual codes contain features of objects, such as colour, in visuospatial capacity. It is possible that the verbal interference in the present experiment interfered with categorical-verbal codes yet the observed categorical advantage was derived from categorical-perceptual components. Therefore, the following experiment is designed to interfere with categorical representations by intruding on both of the subcomponents, and to observe whether coordinate representations would reveal any advantage over categorical representations in VSSTM.

2.4 Experiment 1c: multiple colour, with/without auditory verbal interference

2.4.1 Introduction

This experiment is designed to minimise assistance for categorical spatial relations by interfering with both categorical-verbal and categorical-perceptual codes in visuo-spatial processing. A set of stimuli with different colours was introduced to bind the stimuli’s position information with its identity in visuospatial memory. Dent (2009) also utilised coloured stimuli with articulatory suppression to interfere with visuospatial memory. The results showed that only when stimuli's identity/colour was switched and its position was maintained (i.e. identity-position binding trials) was participants' performance influenced by articulatory suppression. The categorical advantage effect remained when articulatory suppression was applied. That is, even though articulatory suppression affected the process of verbal recoding for objects during VSSTM, categorical spatial processing was still better than coordinate spatial processing. However, the articulatory suppression adopted in Dent's study may not interfere with categorical spatial representations specifically. The current experiment utilised a more sophisticated design, which interferes with categorical-verbal and categorical-perceptual codes independently within categorical representations. The two subcomponents, categorical-verbal and categorical-perceptual codes, could then be interrupted independently through different types of interference words. Specifically, categorical-verbal codes would be interfered with using spatially relevant words while categorical-perceptual codes would be interfered with via colour words. If categorical-perceptual codes contributed to the categorical advantage effect in Exp.1b, one would anticipate that the categorical advantage effect would vanish when colour words were played. Different encoding times and shift sizes were maintained to ensure that categorical information was attenuated and coordinate information was relatively intact during visual-spatial processing.

2.4.2 Methods

2.4.2.1 Participants

Forty-eight healthy young participants were included in the study. Participants were equally divided into four groups: spatial interference group (3 males and 9 females, mean age=23.3, *SD*=3.9), colour interference group (2 males and 10 females, mean age=24.7, *SD*=6.5), irrelevant interference group (4 males and 8 females, mean age=21.0, *SD*=1.9), and no interference/silent group (4 males and 8 females, mean age=21.8, *SD*=3.5). They were aged between 18 and 29 year-old, right-handed and had normal or correct-to-normal vision. The research was approved by the Faculty of Medical Sciences Ethics Committee in Newcastle University.

2.4.2.2 Experiment material, design and procedure

The stimuli set was exactly the same as the previous experiments except the colour of the squares was changed from one colour (red) to multiple colours (red, green, blue, and yellow). The assignment of colour to location was completely randomised. The colours of the four squares were consistent between the encoding and response image in the categorical, coordinate and the same conditions. An additional colour change/switch condition was included. Two of the colours were switched while locations of the squares remained the same in switched trials.

The study was a mixed design as each participant experienced three encoding times (250ms, 500ms, and 2500ms) and three shift sizes (15mm, 20mm, and 25mm) along with one type of interference words (spatially relevant words, colour words, irrelevant words, and no interference). The types of interference were designed as a between-subject variable. The spatially relevant and irrelevant words were identical to Exp.1b and the colour words were "red", "blue", "yellow", and "green". All of the words were pre-recorded and were played to participants repeatedly via headphones throughout the experiment. The experiment procedure was identical to Exp.1b. An example trial procedure is illustrated in Figure 2-10. The retention interval was fixed to 2000ms. There were 48 trials in a block: 12 categorical-change trials, 12 coordinate-change trials, 12 colour switched trials and 12 same trials. Each participant experienced 9 blocks since each retention interval contained three blocks. A short break was provided between blocks. Participants always performed the shortest encoding time first, followed by the medium encoding time, and the longest encoding time was performed last. They were also instructed to utilise their left or right index fingers to press the key "z" or "m" on the keyboard; the assignment of key to response was counterbalanced over participants. Both accuracy and reaction times were recorded by E-Prime software. The experiment duration was approximately 50 minutes.

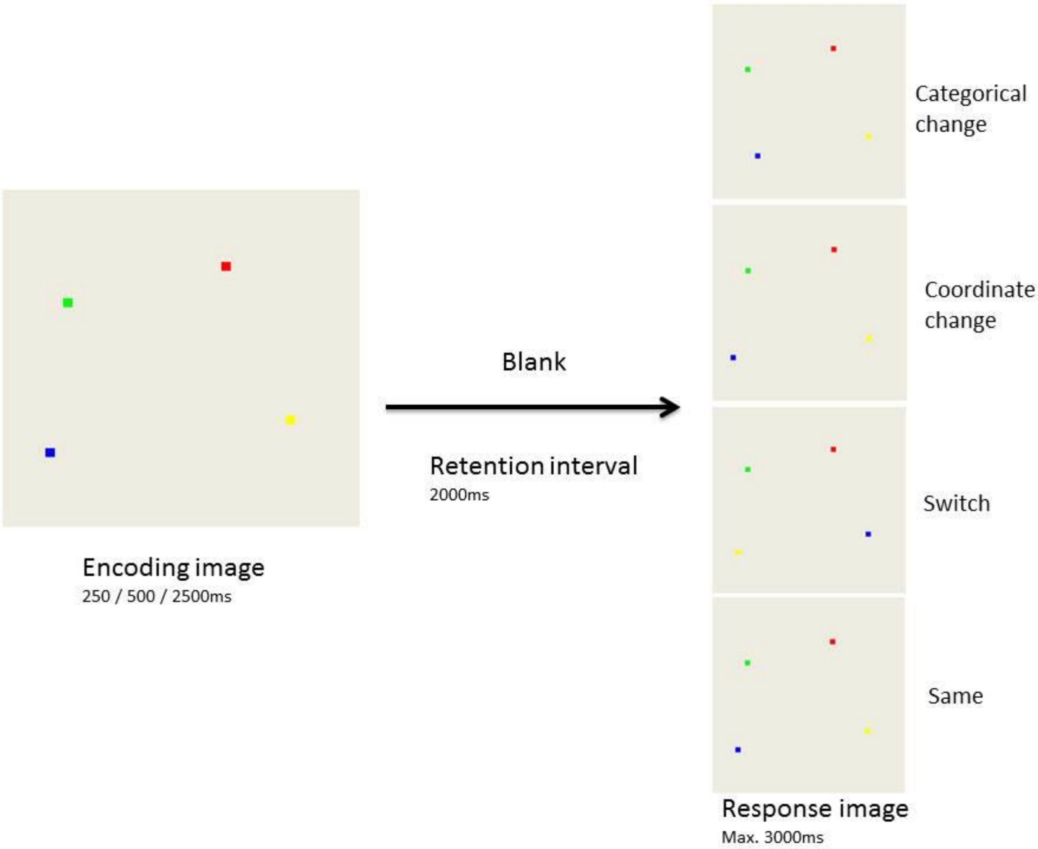


Figure 2-10. Example stimuli and a trial procedure for Exp.1c. The green square on the top left is the reference and the blue square at the bottom left is the target in this example. In a categorical-change trial, the target would be shifted from the left of the reference to the right. In a coordinate-change trial, the target remains to the left of the reference but the distance has been changed. In a switched trial, the position of the target remains the same but the colour is switched to yellow. The colour and position of the squares remain the same in a same trial.

2.4.2.3 Data analysis

Similar to the previous experiments, two analyses were applied. A 4(condition: categorical vs. coordinate vs. switched vs. same condition) × 3 (encoding: 250ms vs. 500ms vs. 2500ms) within-subject repeated measures combined with a between-subject variable (interference type: colour vs. spatial vs. irrelevant vs. no interference) ANOVA was adopted in the first analysis to investigate whether duration of encoding times and/or different types of verbal interference would affect performance on spatial judgments. Results report mainly on interactions between condition and encoding time, and condition and interference type as well as main effects of condition, encoding time, and interference type. The second analysis aimed to observe the impacts of shift size (15mm, 20mm, and 25mm), encoding time and interference type on the performance of categorical and coordinate spatial relations. A four-way ANOVA: 2 (spatial relation: categorical vs. coordinate relation) × 3 (retention interval: 500ms vs. 2000ms vs. 5000ms) × 3 (shift size: 15mm vs. 20mm vs. 25mm) within-subject repeated-measures combined with a between-subject variable (interference type: colour vs. spatial vs. irrelevant vs. no interference) was performed. The same and switched conditions were excluded from this analysis as no spatial shift was manipulated. Interactions between spatial relations with the other three variables, encoding time, shift size, and interference type, and main effects of these variables are reported in the results section. Other interactions will be provided in the Appendix.

2.4.3 Results

Figure 2-11 illustrates accuracy in performance of categorical-change, coordinate-change, the same and colour switched trials, with different interference types and different encoding times. The results showed that neither the interaction of condition and encoding time ($F(6,264)=1.38$, $p=0.222$) nor condition and interference type ($F<1$) was significant. Different encoding times and types of interference words did not affect performance on the categorical, coordinate, same, or switched conditions. The main effect of condition was significant ($F(3,132)=80.38$, $p<0.001$). The same trials showed the best performance (79.5%), followed by switch trials (71.2%), categorical-change trials (54.0%), and coordinate-change trials were performed the worst (37.5%). The effect of encoding time was also significant ($F(2,88)=11.24$), $p<0.001$), indicating that longer encoding times resulted in better memory performance. The 2500ms encoding time showed better memory performance (63.2%) than the 500ms encoding time (60.0%) and the 250ms encoding time (58.4%) while there were no difference between the latter two. The types of interference did not affect performance ($F<1$). None of the interference types influenced spatial judgments. Especially, neither spatially relevant words nor colour words affected the superior role of categorical spatial representations in VSSTM.

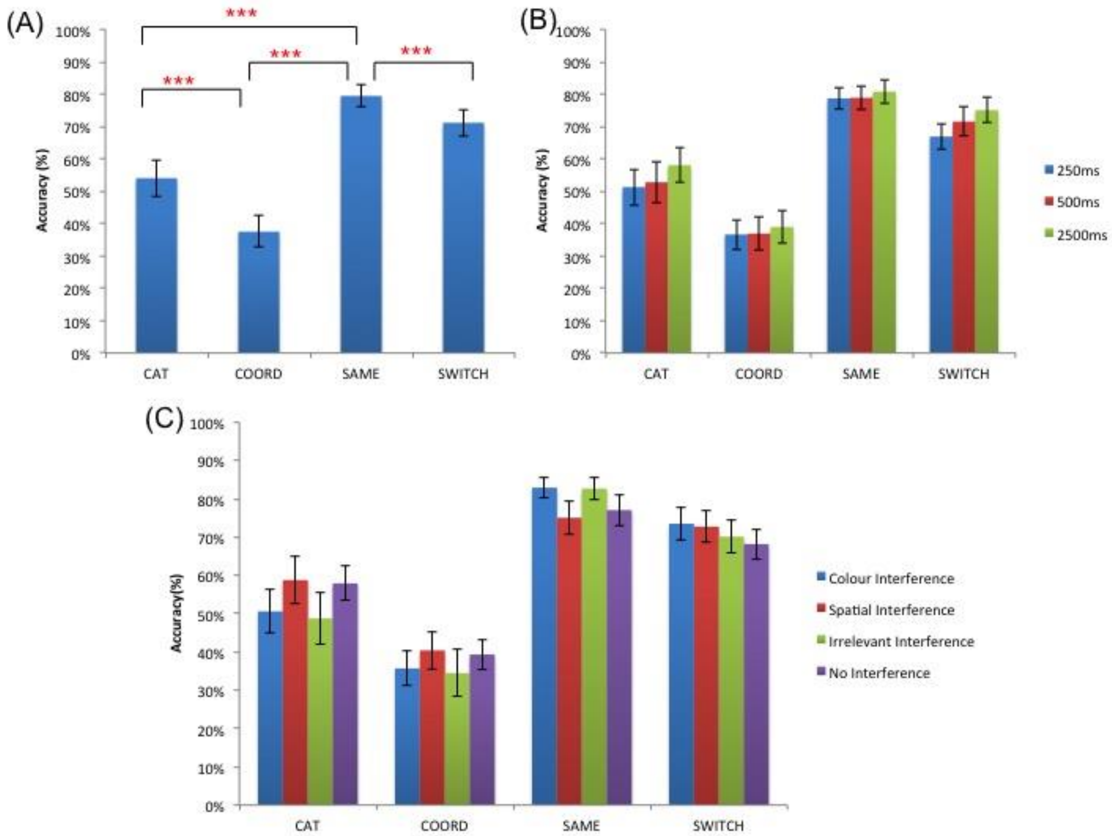


Figure 2-11. Mean accuracy of (A) the four conditions: categorical, coordinate, same, and switched condition, (B) the four conditions with the three encoding times (250ms, 500ms, 2500ms), and (C) the four conditions with the four interference types (colour interference, spatial interference, irrelevant interference, and no interference). '***'=*p* <0.001.

Figure 2-12 depicts reaction times for the four conditions (i.e. categorical-change, coordinate-change, same, and switched condition), performance in the colour, spatial, irrelevant, and no interference type and in the three different encoding times. The results revealed an interaction between condition and encoding time ($F(6,258)=2.99$, $p=0.008$). Post hoc analysis indicated that the four conditions consistently showed significant faster responses in the 250ms and 500ms encoding time than the 2500ms encoding time ($ps<0.001$). However, responses in the 250ms and 500ms were not different from each other. There was no interaction between condition and interference type ($F<1$), indicating that type of interference did not affect categorical, coordinate, same, or switch judgments. The main effect of encoding time was significant ($F(2,86)=69.08$, $p<0.001$). Post hoc analysis indicated that the longest encoding time showed the slowest response times (1386ms) while the medium encoding time and the shortest encoding time were not significantly different in response time (1084ms vs. 1125ms). However, there was no effect caused by condition (*F*(3,129)=1.88, *p*=0.136). Participants showed similar response times for categorical-change, coordinate-change, same, and switch trials. The effect of interference type was also not significant (*F*(3,43)=1.04, *p*=0.385). Types of interference words did not affect response times on the four conditions.

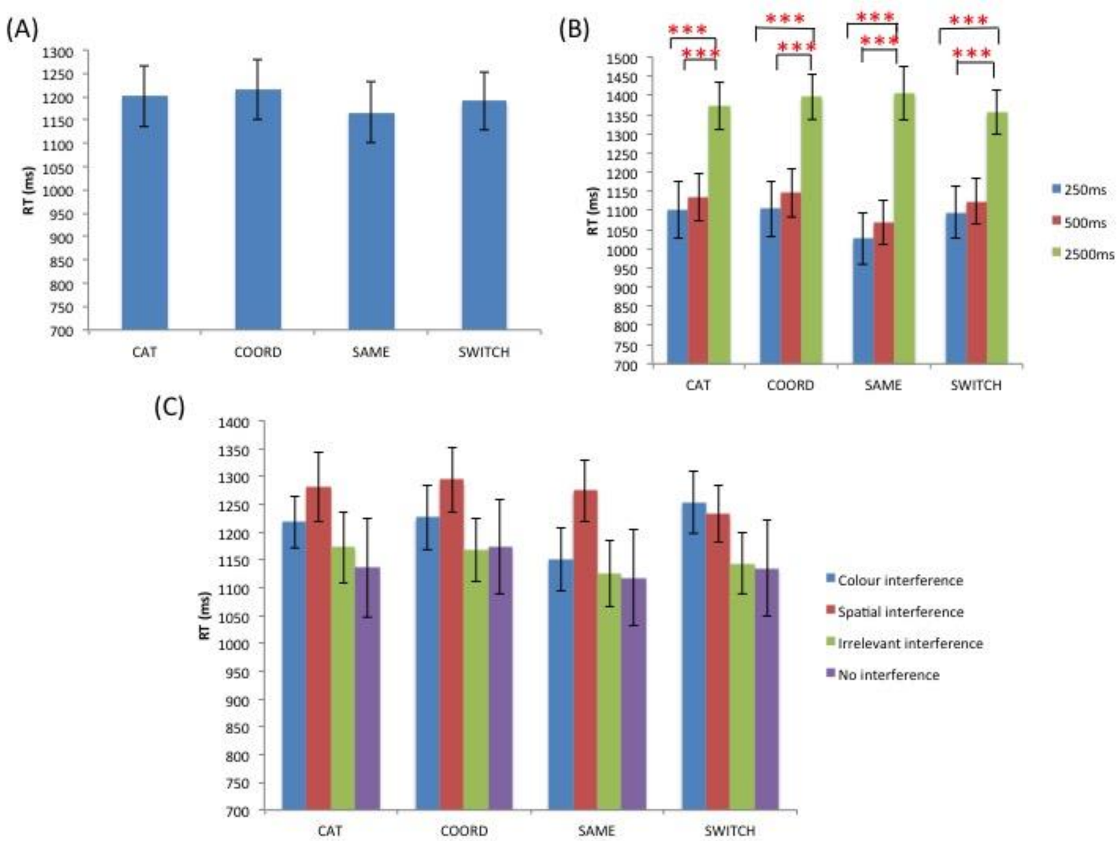


Figure 2-12. Mean reaction times of (A) the four conditions: categorical, coordinate, same, and switch condition, (B) the four conditions with the three encoding times (250ms, 500ms, and 2500ms), and (C) the four conditions with the four interference types (colour interference, spatial interference, irrelevant interference, and no interference). '***'=*p* <0.001.

The second analysis addresses performance of categorical and coordinate spatial relations in different encoding times (250ms, 500ms, and 2500ms), shift sizes (15mm, 20mm, and 25mm), and interference types (colour, spatial, irrelevant, and no interference) (See Figure 2-13). The results showed that there was a significant interaction between spatial relation and shift (*F*(2,88)=14.57, *p*<0.001). Post hoc analysis suggested that the greatest shift size

(25mm) showed the best accuracy of performance, followed by the 20mm shift, and the smallest shift size was performed the worst in categorical-change trials ($F(2,143)=3.76$, $p=0.026$) and coordinate-change trials ($F(2,143)=21.67$, $p<0.001$). However, the interactions between spatial relation and encoding time ($F(2,88)=1.79$, $p=0.173$), and spatial relation and interference type ($F<1$) were not significant. There was no significant difference between performance in the categorical and coordinate condition with different encoding times or types of interference words. A significant main effect of spatial relation was found ($F(1,44)=111.09$, $p<0.001$). The categorical condition (54.0%) was performed better than the coordinate condition (37.5%). Moreover, significant main effects of shift size and encoding time were also found ($F(2,88)=78.84$, $p<0.001$ and $F(2,88)=3.40$, $p=0.038$, respectively). Post hoc analysis indicated that the largest shift size was performed the best (54.3%), followed by the medium shift size (45.1%), and the smallest shift size showed the worst performance (37.9%). Greater shift sizes were easier to detect, resulting in better memory performance. The effect of encoding time suggests that stimuli with longer presentation time result in better memory performance. Specifically, the 2500ms encoding time (48.5%) was memorised significantly better than the 500ms encoding time (44.8%) and the 250ms encoding time (44.0%) while performance for the latter two did not differ from each other. There was no effect of interference type ($F<1$), which indicates that performance for categorical- and coordinate-change trials was not affected by types of interference words.

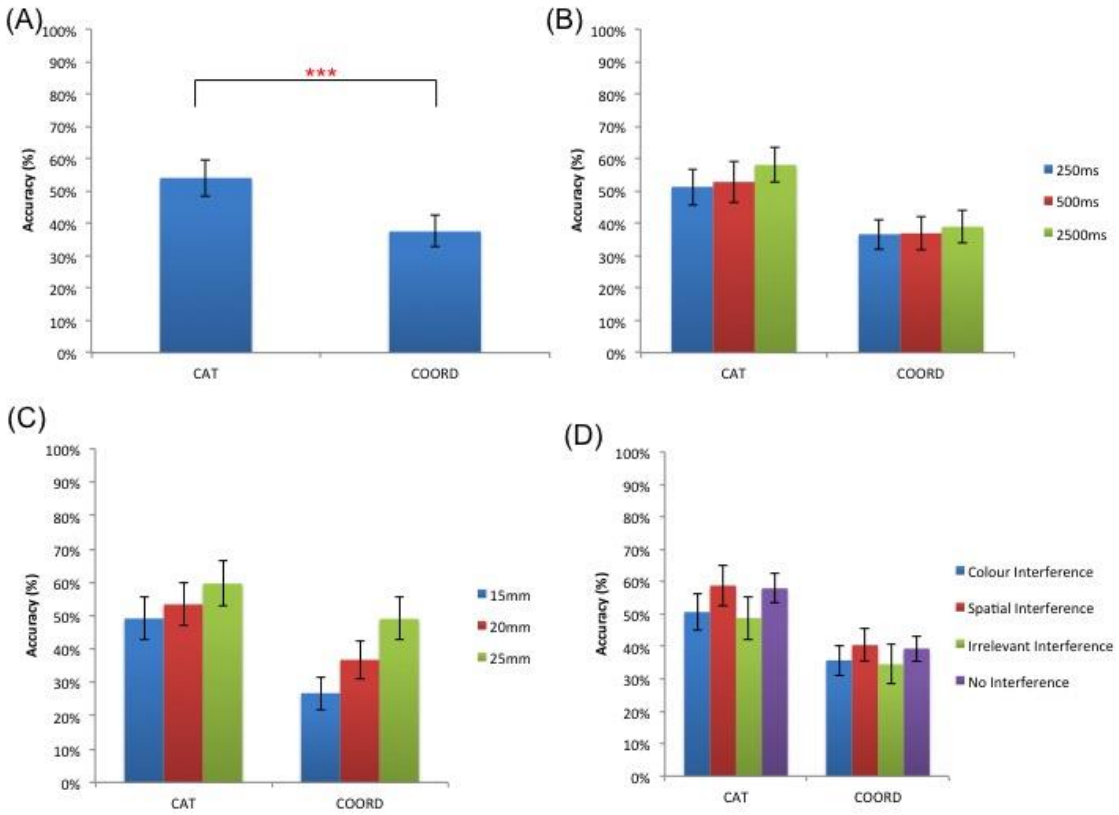


Figure 2-13. Mean accuracy of (A) categorical and coordinate spatial relations, (B) the two spatial relations with the three encoding times (250ms, 500ms, and 2500ms), (C) the two spatial relations and the three shift sizes (15mm, 20mm, and 25mm), and (D) the two spatial representations with the four interference types (colour interference, spatial interference, irrelevant interference, and no interference). '***'=p<0.001.

In terms of reaction times, none of the interactions between spatial relation and shift size (F<1), spatial relation and encoding time (F<1), or spatial relation and interference type ($F(3,30)=1.41$, $p=0.259$) were significant (see Figure 2-14). Participants showed similar reaction times on judging categorical- and coordinate-change trials regardless of the duration of stimuli presentation, shift size or type of interference words. There was a main effect of spatial relation ($F(1,30)=4.71$, $p=0.038$). The responses for categorical-change trials (1165ms) were significantly faster than coordinate-change trials (1195ms). Moreover, the main effect of shift size was significant ($F(2,60)=11.84$, $p<0.001$). Participants responded much quicker to the greatest shift size (1139ms) than to the smallest and the medium shift size. However, there was no significant difference between the smallest and the medium shift size (1216ms vs. 1185ms). In addition, the main effect of encoding time was also significant ($F(2,60)=29.93$, $p<0.001$). Post hoc analysis showed that the longest encoding time resulted in the slowest response times. However, responses to the shortest and the medium encoding times did not differ from each other (1106ms vs. 1095ms). There was no significant effect of interference type, suggests that response times were not affected by types of interference words ($F(3,30)=1.50$, $p=0.235$).

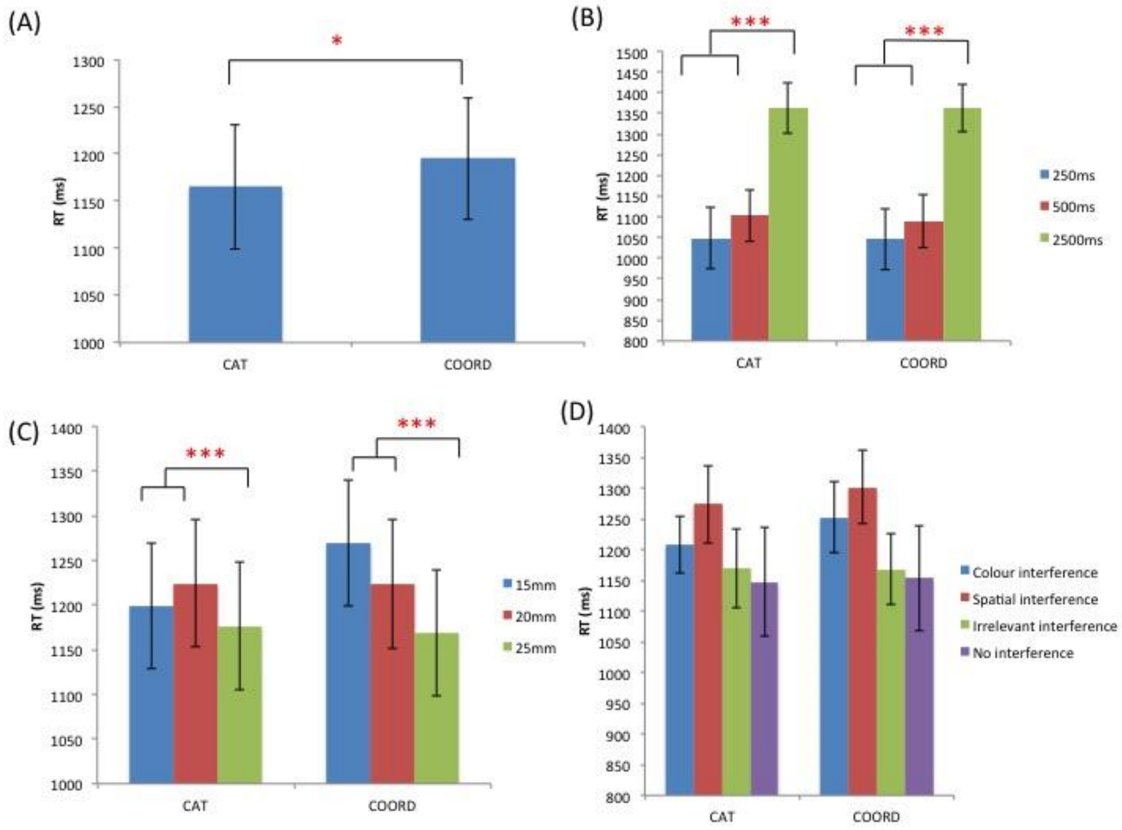


Figure 2-14. Mean reaction times of (A) categorical and coordinate spatial relations, (B) the two spatial relations with the three encoding times:250ms, 500ms, and 2500ms, (C) the two spatial relations and the three shift sizes: 15mm, 20mm, and 25mm, and (D) the two spatial representations with the four interference types: colour interference, spatial interference, irrelevant interference, and no interference. '*'=$p<0.05$ and '***'=$p<0.001$.

Overall, the categorical advantage effect was found in the current experiment. Neither spatially relevant nor colour relevant words intruded on categorical representations since detection of categorical changes was still better and much faster than coordinate changes.

2.4.4 Summary and discussion of Experiment 1c

The present experiment has further extended previous studies by adopting position-identity binding stimuli (i.e., coloured stimuli) to investigate the effects of the two categorical subcomponents, categorical-verbal and categorical-perceptual codes, in the CATCOORD task. The interference of spatially relevant words was designed to interrupt categorical-verbal codes whereas colour words were designed to interrupt categorical-perceptual codes. Nonetheless, the categorical advantage effect was consistently found even when spatially relevant words or colour words were played to participants throughout the experiment. The current results demonstrate that categorical-verbal and categorical-perceptual interferences did not influence the superior categorical spatial processing in VSSTM. Importantly, even when categorical information was minimised, e.g. trials with the shortest encoding time and the smallest shift size, and verbal interference was maximised, e.g. interruptions started from the beginning of the encoding stage of the memory process, categorical-change trials were still performed better than coordinate-change trials in the spatial and colour interference conditions.

In Experiment 1b, verbal interference of spatially relevant words did not affect performance of categorical spatial judgments more than coordinate. Yet the observed categorical advantage may be caused by the categorical-perceptual codes which remained in use while categorical-verbal codes were interrupted. This experiment hence interfered with categorical-verbal and categorical-perceptual coding independently with the coloured stimuli via spatially relevant and colour words in the CATCOORD task. The results still showed the categorical advantage effect, which suggests that categorical spatial relations are dominant in visuospatial representations. One possible reason for the finding may be due to weak interruption of categorical representations by the auditory verbal interference. Future studies which intend to enhance the intervention of categorical spatial representation and to examine the role of coordinate spatial representation in VSSTM could apply a stronger interference task to categorical representation, such as spatial tapping. Another possibility is that the existence of the categorical advantage effect may be due to the design of the auditory verbal interference. Participants repetitively heard four pre-recorded interference words in the same order which may lead to them habituating and to the development of a memory strategy, such as to ignore the words; hence the impacts of the interference words were minimal. To play interference words less predictably may draw participants' attention to the interference words throughout visuospatial processing and maximise the effect of interference in VSSTM.

Overall, the current study has extended previous findings by demonstrating the categorical advantage effect when the two subcomponents, categorical-verbal and categorical-perceptual codes, were interrupted. The notion that categorical spatial representations are an intrinsic property of visuospatial memory whilst coordinate spatial representations are a supplementary visual-spatial process in VSSTM is supported by these results.

2.4.5 Summary of Experiment 1a-1c

This section will summarise the findings from the CATCOORD task. The implications will be addressed in a later section (see section 2.6). The three behavioural experiments in Experiment 1 have consistently found a robust categorical advantage effect regardless of encoding times, retention intervals, and shift sizes. Moreover, when categorical-verbal and categorical-perceptual codes were interrupted during visuo-spatial processing, categorical changes between objects were still easier to detect than coordinate changes. Even though the behavioural experiments did not show sensitivity to time courses for coordinate spatial relations, separable spatial relations in VSSTM have been demonstrated with the whole visual-field task, the CATCOORD task. Although categorical spatial representations showed better memory performance than coordinate spatial representations in VSSTM, the underlying neural mechanisms of the two spatial relations may reveal a different story. Previous literature has demonstrated hemispheric specialisations for the two spatial representations, thus the following section will investigate lateralisation effects in the CATCOORD task with a neuroimaging technique.

2.5 Experiment 2: CATCOORD Neuroimaging study

2.5.1 Introduction

The current experiment incorporated functional Magnetic Resonance Imaging (fMRI) to investigate the underlying mechanisms of categorical and coordinate spatial processes. This technique observes correspondent processing regions when undertaking categorical or coordinate spatial relations via changes of blood flow in the brain. Although previous behavioural experiments did not demonstrate the coordinate advantage in short time courses of encoding and retention interval, the underlying mechanisms may still show hemispheric lateralisation effects for the two spatial relations. Increased activation in the right hemisphere may be found when processing the coordinate spatial representation while greater activations in the left hemisphere may be associated with categorical spatial processing.

Previous fMRI studies which have demonstrated the lateralisation effects of the two spatial representations usually utilised a block design with a half visual-field task (Slotnick & Moo, 2006; van der Ham et al., 2009). For instance, van der Ham et al. (2009) utilised a dot-cross half visual-field task to observe categorical and coordinate spatial processing with fMRI. Two maintenance intervals (500ms and 2000ms) were manipulated in the half visual-field task. Similar to their previous study (van der Ham et al., 2007), the behavioural results showed the lateralisation effects in the short maintenance interval. Importantly, they also demonstrated the hemispheric effects for the two spatial relations in neuroimaging results during the long maintenance interval. Left superior parietal regions showed greater neural activity when processing categorical judgements while right superior parietal regions showed greater neural activity when processing coordinate judgments. Slotnick and Moo (2006) utilised a similar paradigm with a dot and an abstract shape to observe prefrontal activations when processing categorical and coordinate spatial relations. The left prefrontal cortex showed greater activation during categorical than coordinate processing while the right prefrontal cortex showed greater activation during coordinate processing, compared with categorical processing. Both studies utilised a block design, which means participants undergo the same type of spatial judgment for a period, and have demonstrated a hemispheric specialisation effects for the two spatial relations. A drawback of a block design is that the instructions are fixed for the type of spatial judgment. An event-related design allows types of spatial judgments to be cued on each occasion hence it is thought to be a preferable method. The present experiment adopts an event-related design with the CATCOORD task to examine the hemispheric lateralisation effects when types of spatial judgement are unforeseeable and when the stimuli are presented in the whole visual field.

2.5.2 Methods

2.5.2.1 Participants

Twelve healthy young participants were recruited to the study (6 males and 6 females, mean age=27.1, *SD*=5.7). None of them had participated in any of the previous experiments. All subjects were right-handed and reported no previous history of psychiatric disorders or substance misuse. All subjects were given a consent form and received a financial reward of £20 after completing the experiment. The research was approved by the Faculty of Medical Sciences Ethics Committee in Newcastle University.

2.5.2.2 Experiment material, design and procedure

The stimuli were identical to Experiment 1a. The CATCOORD task consisted of a set of unicolour stimuli, which encouraged participants to rely on position-only information when processing the spatial relations. Stimuli with only position information limited the characteristics of categorical spatial representations and led participants to utilise other features in the visual-spatial array. This experiment was the first one which utilised a whole visual-field task to investigate categorical and coordinate spatial processing with fMRI. An event-related design was utilised to associate acquired blood-oxygen-level dependent (BOLD) signals to types of spatial judgments based upon trials. The number of trials in each block was increased to 54 (18 categorical-change trials, 18 coordinate-change trials, and 18 same trials) to enhance detected neural signals for categorical and coordinate spatial processing. Three blocks were performed in the scanner and the trials within each block were randomly presented. A fixation cross (1000ms), an encoding image (500ms), a retention interval (2000ms), and finally a response image (up to 3000ms) were presented to participants sequentially within a trial. The manipulation of the three shift sizes (15mm, 20mm, and 25mm) was maintained in the fMRI experiment. Presentation® software (Version

14.7, www.neurobs.com) was utilised to present the stimuli and to record responses. The stimuli were projected onto a rear-projection screen via a pico projector located at the head of the scanner and were visible via an overhead mirror. Participants were asked to indicate a “same” or “different” judgement using the index or middle finger of their right hand via an fMRI-compatible button box upon presentation of the response image. Subjects were given a 10-second break between blocks of trials and were also able to rest between runs. Six practice trials were provided to participants before entering the scanner in order to acclimatise them to the time course of stimulus presentation and mode of response.

2.5.2.3 Data analysis

2.5.2.3.1 Behavioural data

A within-subject repeated-measure ANOVA was performed to analyse accuracy and reaction times of the three conditions (categorical changes vs. coordinate changes, vs. same). The second analysis consisted of a 2 (categorical vs. coordinate changes) × 3 (15mm vs. 20mm vs. 25mm) within-subject repeated-measure ANOVA to observe the effect of shift sizes on the two spatial representations.

2.5.2.3.2 Imaging data

Images were acquired on a 3-Tesla Philips Intera Achevia MRI system. For functional scans a single-shot EPI sequence was used and MR acquisition parameters were as follows: TE=30ms; TR=2600ms; FOV (right-left, anterior-posterior, foot-head)=200*200*140 mm; flip angle=650; voxel size=3x3x3.5mm^3). T1-weighted structural images were acquired before the run of functional scans began.

Imaging processing and statistical analysis was performed with SPM8 software (www.fil.ion.ucl.ac.uk). Firstly, the images underwent slice-time correction during pre-processing to account for differences in slice acquisition. To remove movement artefacts within the images, realignment and unwarping processing co-registered images to the first scan of the block. Normalisation steps registered unwarped images to a standard MNI template before images underwent smoothing with an 8mm full-width half-maximum Gaussian kernel to limit the differences in neuroanatomy between subjects.

First-level analysis applied a general linear model to estimate the related BOLD responses across four conditions, separated into correctly and incorrectly answered trials: categorical trials, coordinate trials, same trials and the encoding of each trial. The high-pass filter was set at 128s to reduce low-frequency noise. Movement parameters were included in the model to reduce movement related artefacts.

A flexible factorial design was applied in a second-level statistical analysis; only scans for correct answered trials were included in the analysis. Cluster activations, relative to activity at fixation baseline, in the "categorical-correct" and "coordinate-correct" conditions were deemed significant if a $p<0.05$ (Family-Wise Error correction) was achieved. Contrast images were created to compare activity in the "categorical-correct" and "coordinate-correct" conditions; significance was determined if $p<0.001$ (uncorrected). The Automatic Anatomical Labelling toolbox for SPM8 was used to identify areas of cluster activation.

2.5.3 Results

2.5.3.1 Behavioural results

Figure 2-15 shows the behavioural results for accuracy of the categorical, coordinate, and same conditions. There was a main effect of condition ($F(2,22)=6.23$, $p=0.007$), the same condition was performed significantly better than the categorical condition (82.9% vs. 70.2%; $t(11)=2.65$, $p=0.022$) and the coordinate condition (82.9% vs. 68.7%; $t(11)=2.70$, $p=0.021$) while the performance of the latter two conditions did not differ from each other ($t(11)=0.55$, $p=0.596$). The categorical advantage effect, which was consistently found in the behavioural experiments, was not found in the fMRI study.

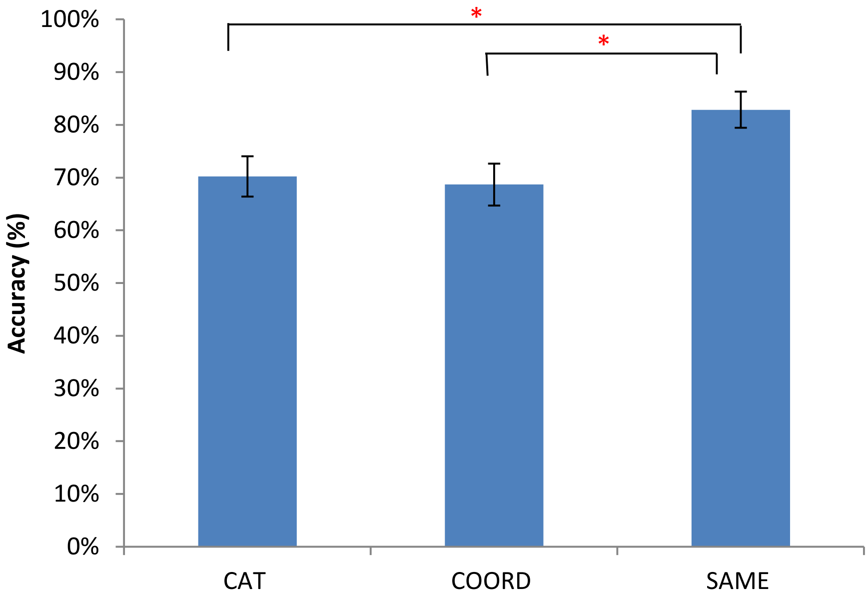


Figure 2-15. Accuracy of performance for the categorical, coordinate, and same conditions in the CATCOORD neuroimaging study. '*'=$p<0.05$.

Figure 2-16 presents the mean reaction times. There was a main effect of condition ($F(2,22)=7.28$, $p=0.004$). Post hoc analysis indicated that responses in the same condition were significantly slower than the categorical condition (1394ms vs. 1190ms; $t(11)=3.27$, $p=0.007$) and the coordinate condition (1394ms vs. 1174ms; $t(11)=2.61$, $p=0.024$). The difference between responding to categorical and coordinate changes trials was not significant ($t(11)=0.42$, $p=0.681$). Although the same trials showed the best performance among the three conditions, they also required longer reaction time. The categorical and coordinate conditions obtained similar response times in the scanner.

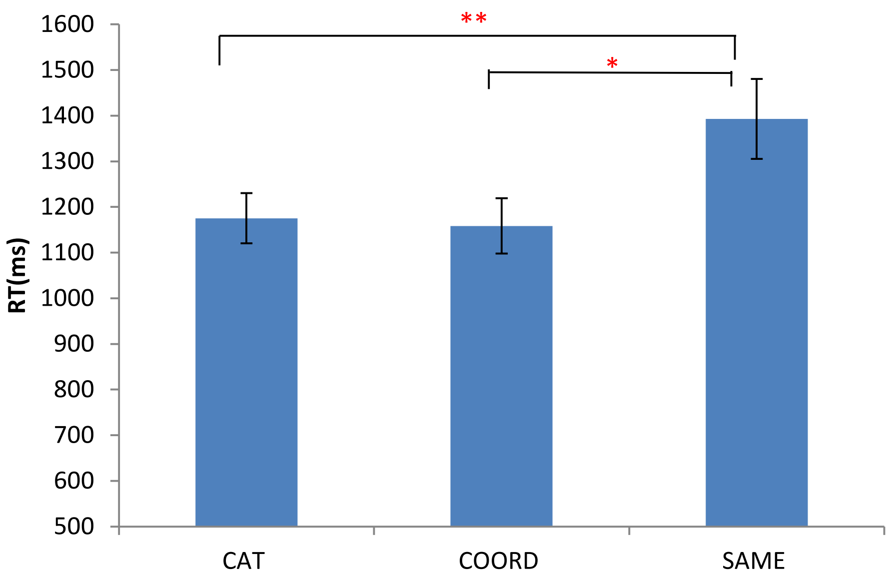


Figure 2-16. Reaction times for the categorical, coordinate and same conditions in the CATCOORD neuroimaging study. '*'=p<0.05; '**'=p <0.01.

Figure 2-17 illustrates accuracy of performance between the two spatial relations (categorical and coordinate spatial relations) with the three shift sizes (15mm, 20mm, and 25mm). Categorical- and coordinate-change trials performed similarly in the scanner (F<1). A significant effect of shift size was found ($F(2,22)=84.29$, $p<0.001$). Post hoc analysis indicated that the largest shift size was performed the best (85.0%), followed by the intermediate shift size (75.7%), and the smallest shift was performed the worst (47.7%) (ps £0.001). There was no interaction between spatial relation and shift size ($F(2,22)=2.22$, $p=0.132$). Even though the categorical advantage effect vanished, the effect of shift size was still observed. Participants performed better when the shift size was greater.

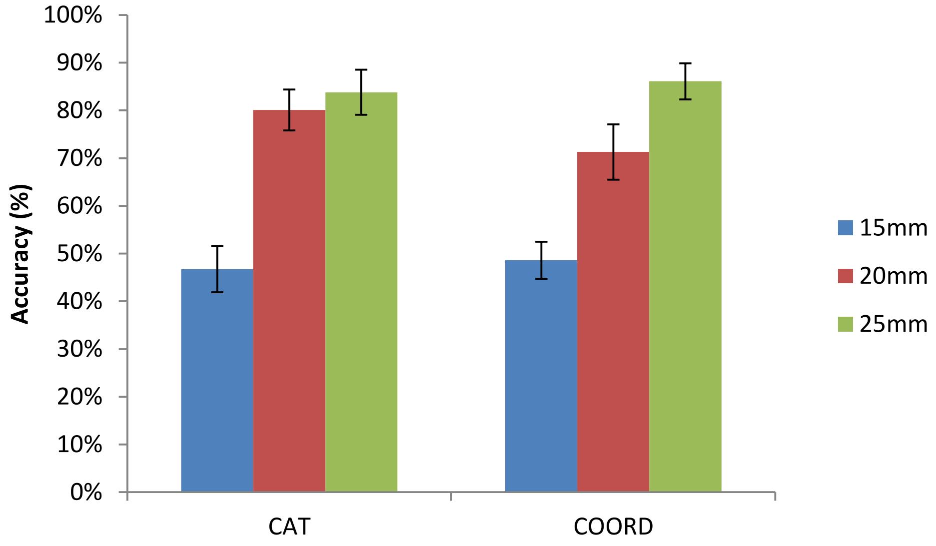


Figure 2-17. Accuracy of performance for the categorical and coordinate conditions with the three shift sizes in the CATCOORD neuroimaging study.

Figure 2-18 shows reaction times for categorical- and coordinate-change trials with the three shift sizes. The main effect of spatial relation was not significant (F<1). Participants showed similar response times regardless of categorical or coordinate spatial changes. However, the main effect of shift size was significant ($F(2,22)=11.50$, $p<0.001$). The smallest shift size was responded to significantly slower than the intermediate shift size (1321ms vs. 1133ms; $t(11)=3.44$, $p=0.006$) and the greatest shift size (1321ms vs. 1092ms, $t(11)=3.56$, $p=0.004$) yet the difference between the two larger shift sizes was non-significant ($t(11)=1.58$, $p=0.143$). The small shift between objects was difficult to detect in the visual-spatial array. Although longer reaction times were obtained when detecting small shift changes, accuracy was still poor. There was no interaction between spatial relation and shift size (F<1).

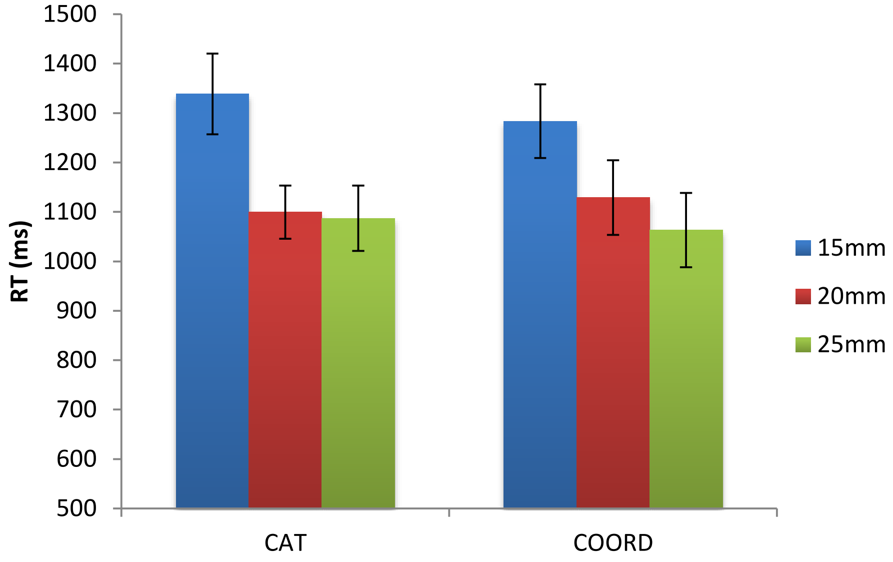


Figure 2-18. Reaction times for the categorical and coordinate conditions with the three shift sizes in the CATCOORD neuroimaging study.

2.5.3.2 Neuroimaging results

Contrasts between the categorical vs. the same and the coordinate vs. the same conditions were performed to observe additional neural activities for the spatial relations. The voxel-based comparisons for the categorical and coordinate conditions compared to the same condition are depicted in Figure 2-19 and described in Table 2-2 (*p*<0.001; uncorrected). Note that the effects of the contrasts were weak hence a looser uncorrected adjustment was applied to observe subtle differences. The right hemisphere revealed greater neural activity when processing categorical- and coordinate-change trials than same trials. The categorical condition involved greater frontal and parietal regions during the spatial processing. Specifically, bilateral inferior parietal lobule, right precuneus, and right inferior and middle frontal gyrus showed significantly greater neural activity in the categorical than the same condition. However, only a few regions of the frontal lobe, right postcentral gyrus and right precentral gyrus, showed greater activations in coordinate spatial processing than in the same condition (Table 2-2).

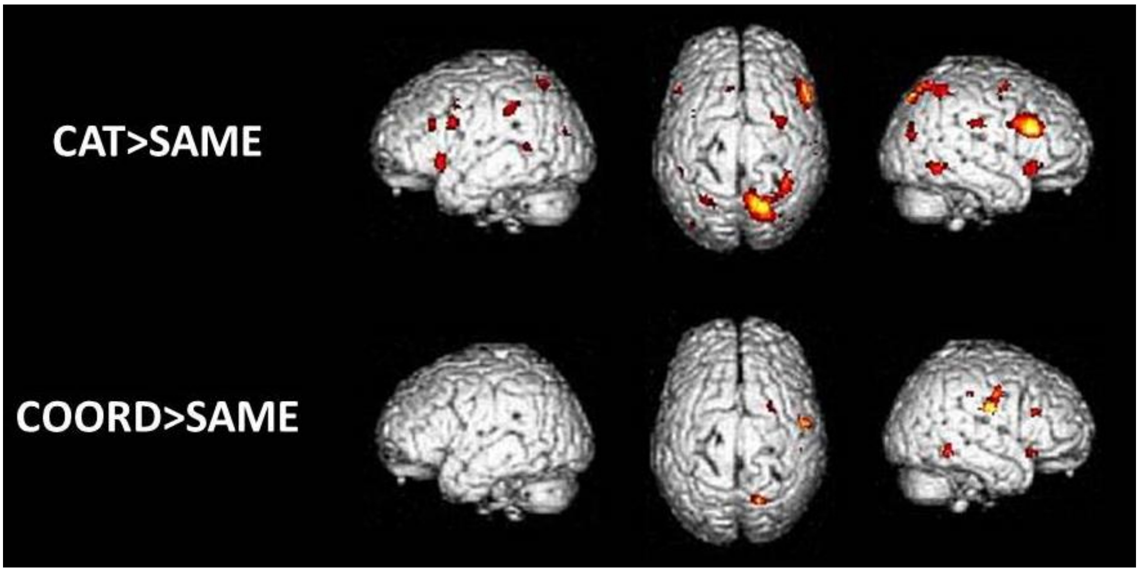


Figure 2-19. Glass brain images for the contrasts of the categorical or coordinate condition vs. the same condition (results threshold uncorrected, $p<0.001$, $k\geq10$).

Table 2-2. Top clusters for the whole brain analysis for the CAT>SAME and COORD>SAME contrasts (uncorrected, $p<0.001$, $k\geq10$).

Region	Local peak	Cluster (voxels)	t-value (peak)	Mean Z (peak)	MIN mm (x,y,z)
		CAT>SAME			
Parietal	R superior parietal lobule	780	6.61	4.86	(12,-66,58)
	R precuneus		6.07	4.61	(18,-68,52)
	L inferior parietal lobule	252	5.51	4.32	(-44,-38,36)
	L sub-gyral		4.59	3.80	(-36,-38,34)
Frontal	R inferior frontal gyrus	577	6.65	4.87	(48,24,24)
	R sub-gyral		5.32	4.22	(40,26,18)
	R inferior frontal gyrus	170	5.92	4.53	(32,22,-10)
	L middle frontal gyrus	148	4.99	4.04	(-34,4,38)
	L sub-gyral		4.42	3.70	(-38,8,24)
		COORD>SAME			
Frontal	R postcentral gyrus	181	5.57	4.36	(54,-12,26)
	R precentral gyrus		4.48	3.74	(54,-10,38)

2.5.3.2.1 Exploratory analysis

The previous analysis provided limited information when comparing categorical and coordinate spatial processing and no spatial change/same processing. The differences were revealed only when the correction criteria was less restricted. Therefore, the exploratory analysis compared the categorical and coordinate processes with resting status, i.e. baseline, when participants saw a blank screen and were not involved in visual-spatial processing. Differences in processing categorical and coordinate spatial relations may emerge in the comparison with the baseline. Figure 2-20 illustrates comparisons for categorical vs. baseline and coordinate vs. baseline, and their ROIs are presented in Table 2-3 (FWE corrections, $p<0.05$). Both categorical and coordinate spatial processing revealed bilateral activations when compared to the baseline. In fact, the underlying neural networks were very similar when processing categorical and coordinate spatial relations. The categorical spatial processing involved more brain regions than the coordinate spatial processing. While left inferior parietal lobule and left middle frontal gyrus were involved when processing both spatial relations, right inferior frontal gyrus, right sub-gyral in temporal lobe and left cuneus in occipital lobe were additionally found in the categorical spatial processing. When comparing the categorical and coordinate spatial processing directly, right precuneus region showed a trend of stronger neural activity when processing categorical than coordinate spatial judgments (cluster result uncorrected, $k=44$, $t=4.34$, $p=0.056$).

Although the hemispheric effects for the two spatial representations were not observed in the CATCOORD task, the neural imaging results still showed a difference between the two spatial processes. Categorical spatial processing involved more parietal and frontal regions and stronger neural activities than coordinate spatial relations.

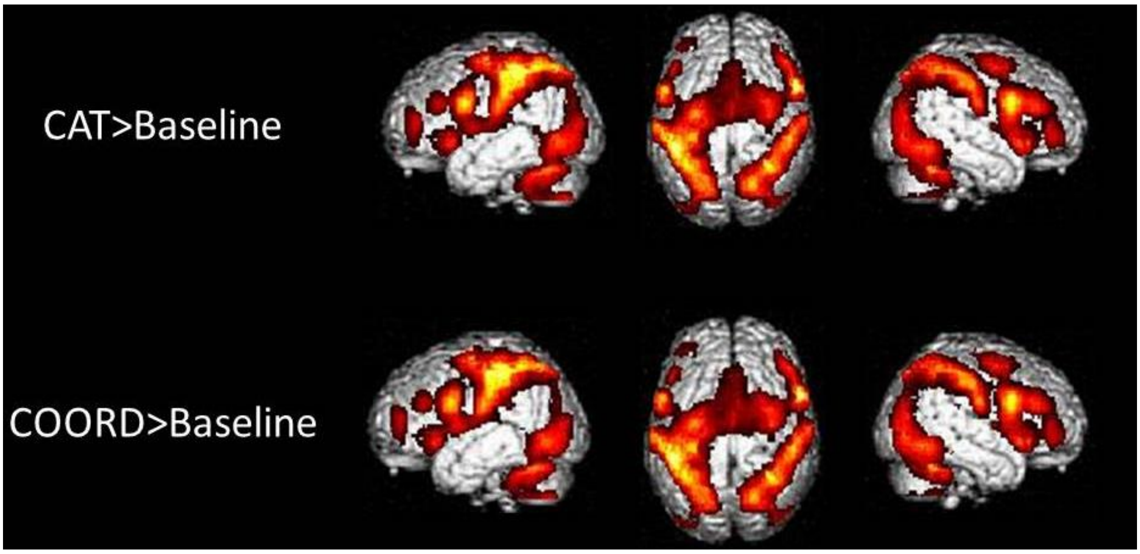


Figure 2-20. Contrasts of categorical or coordinate condition vs. baseline (resting state) (FWE corrections, *p*<0.05).

Table 2-3. Top clusters for the whole brain analysis for the CAT>Baseline and COORD>Baseline contrasts (FWE corrections, *p*<0.05, *k*≥10).

Region	Local peak	Cluster (voxels)	t-value (peak)	Mean Z (peak)	MIN mm (x,y,z)
		CAT>Baseline			
Parietal-frontal	L inferior parietal lobule	47152	40.86	Inf	(-44,-40,52)
	L middle frontal gyrus		38.31	Inf	(-26,-12,62)
	R inferior frontal gyrus		38.22	Inf	(56,12,32)
Frontal	L middle frontal gyrus	476	14.9	7.21	(-34,46,14)
	L sub-gyral		13.8	7	(-36,46,6)
Occipital	L cuneus	102	9.81	6.02	(-20,-74,6)
Temporal	R sub-gyral	11	7.52	5.24	(44,-34,-6)
		COORD>Baseline			
Parietal	L inferior parietal lobule	50325	41.56	Inf	(-44,-38,50)
	L postcentral gyrus		38.92	Inf	(-48,-30,38)
	L precentral gyrus		38.65	Inf	(-26,-12,62)
Frontal	L middle frontal gyrus	419	15.19	7.26	(-34,46,14)
	L sub-gyral		13.19	6.87	(-36,46,6)

2.5.4 Summary and discussion of Experiment 2

Experiment 2 was designed to investigate the underlying neural mechanisms for categorical and coordinate spatial processing with a whole visual field task, the CATCOORD task. This is the first experiment to utilise the CATCOORD task with fMRI to observe neural networks of the two spatial relations. While a block design experiment enables participants to foresee the upcoming spatial judgment type, the event-related design leaves types of spatial judgment unpredictable. Participants are less likely to adopt a memory strategy which is developed by repetitive trials. The results with the event-related design are deemed to be closer to the nature of the spatial representations since participants could not predict types of spatial judgment for the next trial. The behavioural results showed that shift sizes affected spatial judgments on both categorical and coordinate spatial relations. The greater the shift size, the easier it is to detect, resulting in better performance. However, the categorical advantage effect which has been consistently found in the behavioural experiments was not found (see section 2.2.3 (Exp.1a), section 2.3.3 (Exp.1b) and section 2.4.3 (Exp.1c)). Similar performance of categorical and coordinate spatial judgments was observed when the task was carried out inside the scanner. The neuroimaging results did not reveal hemispheric lateralisation processing for the two spatial relations. Similar bilateral activations in frontal and parietal regions were found in categorical and coordinate spatial processing. Moreover, categorical spatial processing showed broader neural network than coordinate spatial processing, suggesting that it is a primary spatial process in VSSTM.

Unlike the previous behavioural experiments, the present behavioural results did not reveal the categorical advantage effect with the CATCOORD task. Coordinate and categorical spatial relations showed similar performance in VSSTM. It is possible that the better coordinate spatial judgments in the fMRI study may be an artefact: any subtle difference between encoding and response image of coordinate changes could become clear when a participant's head is fixed in the scanner. It is suspected that restricted head movement produces visual traces, which provide clues to distinguish subtle spatial changes. Therefore, coordinate changes are easier to detect inside the scanner than outside of the scanner, when the head is not fixed. Categorical spatial judgments, however, maintained their good performance on the task and did not benefit from visual residuals.

The neuroimaging results showed bilateral activation on parietal cortex and cuneus/precuneus, which have been associated with spatial processing in previous studies (Baumann, Chan, & Mattingley, 2012; Martin, Houssemand, Schiltz, Burnod, & Alexandre, 2008; Trojano et al., 2002; van der Ham et al., 2009). The right hemisphere showed greater neural activation when processing spatial judgments than no spatial changes (i.e. the same condition). This supports Dent's finding (2009) in which manipulations of categorical and coordinate spatial changes in the CATCOORD task were different from visual pattern recognition, i.e. polygons judgments. Unlike a previous study which demonstrates hemispheric lateralisation effects with a half visual-field task (van der Ham et al., 2009), the current study suggests that the lateralisation effects vanish when a whole visual field task is adopted. The CATCOORD task revealed similar bilateral activations when processing categorical and coordinate spatial relations. It is possible that the lateralisation effect for the two spatial representations depends on task design, such as half visual-field presentation of stimuli and/or instructions on judgments being provided explicitly to participants. Even though bilateral activations were observed in both spatial processes, greater and broader neural networks were found in categorical than coordinate spatial processing. The notion that categorical spatial representations are an intrinsic property in visuo-spatial representations is supported by neuroanatomical evidence.

The present experiment adopted the CATCOORD task to observe the underlying neural mechanisms of the two spatial relations. Categorical and coordinate spatial representations showed similar behavioural performance as well as neural network activation when participants were unaware of spatial judgment and when stimuli were presented on the whole visual field. The previous findings of hemispheric spatial processing for categorical and coordinate relations may be restricted to a condition where participants are asked to make specific spatial judgments.

2.6 Summary of Chapter 2

The current chapter consists of a series of experiments to observe categorical and coordinate spatial representations in VSSTM with a whole visual-field task, the CATCOORD task. The three behavioural experiments demonstrated that regardless of different time courses during encoding or maintenance stage and types of verbal interference, the categorical spatial representations were always performed better than the coordinate spatial relations. The results support and develop Dent’s findings (2009) in which categorical spatial representations are an intrinsic property in visuospatial memory. Moreover, different shift distances between target and reference were found to consistently affect memory performance in both categorical and coordinate spatial relations, with more apparent sensitivity to distance changes in coordinate relations than categorical relations. The manipulated categorical and coordinate changes in the CATCOORD task could be attributed to visuospatial representation. A characteristic of precise metric spatial changes for coordinate spatial representations has been replicated in the experiment paradigm.

The neuroimaging evidence indicates that bilateral activations occur when processing both spatial relations. The hemispheric lateralisation effects for categorical and coordinate spatial representations that have previously been reported (Slotnick & Moo, 2006; van der Ham et al., 2009) are not found when stimuli are presented on the whole visual field. The separability of categorical and coordinate spatial processes is supported by the broader neural network found in categorical but not coordinate spatial process in Experiment 2. It is important to note that the hemispheric lateralisation effects for spatial processing on a whole visual field task have been demonstrated in patient studies (Gallagher, Gray, Watson, Young, & Ferrier, 2014; Kessels et al., 2000). For example, Kessels and colleagues showed that among ten patients who had undergone intracranial tumour resection and presented secretive spatial memory impairments, two of them were impaired on positional memory performance (i.e. the ability to remember precise, metric spatial information) and another two showed a selective impairment on object location binding and the combined processes (e.g. the ability to remember relative, abstract spatial location) (Kessels et al., 2000). Taking both behavioural (Experiment 1a-1c) and neuroimaging (Experiment 2) evidence together, the results are in agreement with previous literature (Dent, 2009; Kosslyn & Chabris, 1992; Kosslyn, 1987; Niebauer, 2001); categorical relations are primary processes in VSSTM while coordinate relations are subsequent processes. More importantly, present neuroimaging results suggest that the two spatial processes share a similar neural network.

The three behavioural experiments conducted in the current chapter have further extended Dent's findings and indicated that categorical spatial relations are a dominant spatial process in visuo-spatial representation. The categorical advantage effect has been consistently found even when experimental design is unfavourable for categorical spatial processing. Coordinate spatial representation, on the other hand, is thought to be a supplementary visuo-spatial process. Even though previous studies (van der Ham et al., 2009, 2007) have demonstrated that short time courses would reveal coordinate advantage in VSSTM, coordinate relations did not reveal a similar or even better performance than categorical relations in a short encoding time and short retention interval in the current experiment. In the shortest encoding time and maintenance interval and in trials where the shift between objects was the smallest, where the accessibility of categorical information was minimised and coordinate was maximised, categorical-change trials were still performed better than coordinate-change trials. This finding suggests that the coordinate advantage in short time courses disappears when spatial judgments are implicit and when stimuli array is presented on the whole visual field.

Verbal information is one of the characteristics of categorical representations. Experiments 1b and 1c hence adopted verbal interference to intrude on categorical-verbal and categorical-perceptual processes during visuo-spatial processing. Although articulatory suppression is a common interference methodology and has been adopted in previous studies, its effect on spatial memory is inconsistent (Dent, 2009; Kessels & Postma, 2002; Postma & de Haan, 1996; Postma, Izendoorn, & de Haan, 1998; Postma, Winkel, Tuiten, & van Honk, 1999). When utilising an object location memory task, some studies observed interference effects on all conditions; position-only information, object location binding, and combined processes (Postma et al., 1998, 1999) but others showed selective interference effects on some conditions (Kessels & Postma, 2002; Postma & de Haan, 1996). Therefore, the current study adopted a different interference approach. The passive auditory verbal interference is a relatively weak interference method compared to articulatory suppression; however, it is likely to affect exact spatial components. When spatially relevant words and colour words are applied, which represent categorical-verbal and categorical-perceptual codes, the interference with categorical spatial representation is thought to be more precise. Coordinate performance may be similar to categorical performance in VSSTM once the two subcomponents of categorical representations are interfered with. The result still showed better performance of categorical over coordinate spatial relations. Therefore, categorical representation is deemed to be a primary spatial process.

The neuroimaging study was conducted to observe the underlying mechanisms of the two spatial representations. The finding did not support previous studies which have demonstrated hemispheric lateralisation effects for categorical and coordinate spatial representations in fMRI studies (Slotnick & Moo, 2006; Trojano et al., 2002; van der Ham et al., 2009), an ERP study (van der Ham et al., 2010), and an rTMS study (Trojano et al., 2006). Bilateral activation for categorical and coordinate spatial processing was found in the neuroimaging results. The inconsistent finding may be due to different experiment tasks; hemispheric lateralisation effects have emerged when a half visual field task and explicit spatial judgments instructions were applied. The lateralisation effects do not occur in the CATCOORD task, when stimuli are presented on the whole visual field and spatial judgment clues are not provided to participants. It is possible that as soon as participants are aware of types of spatial judgments, a memory strategy is developed. The specificity of the left hemisphere processing categorical relations and the right hemisphere processing coordinate relations is a consequence of the memory strategy. The latter methodology examines whether the lateralisation effects are caused by hemi-field specificity. That is, the lateralisation effects only appear with tasks that present stimuli at different half visual fields.

Bilateral activation was found in the CATCOORD task when processing categorical or coordinate spatial relations. The result indicates that the two spatial relations may share similar neural networks. However, it should be mentioned that similar accuracy of performance and reaction times for categorical- and coordinate-change trials were also found in the neuroimaging study. The robust categorical advantage effect was not found when the task was performed in the scanner. The behavioural result restricts interpretation for the neuroimaging findings. Different experiment conditions (e.g. whether the head is fixed or not) may induce an artefact (e.g. visual residuals on a screen) which benefit coordinate spatial relations. Thus coordinate spatial changes became as apparent as categorical spatial changes. Moreover, experiment environments (e.g. illumination, background noise) could cause inconsistent findings between Experiment 1 and Experiment 2. Future studies could manipulate different environment factors to explore impacts of these factors to the visual-spatial process.

A series of experiments were conducted in Chapter 2 to investigate a possible categorical boundary in VSSTM. The results showed a robust categorical advantage effect in visuospatial representation even when the two subcomponents of categorical representation were interrupted. When stimuli are presented on the whole visual field, the effect of time courses and the hemispheric specificity for categorical and coordinate spatial process does not occur. The results suggest that categorical spatial representation may be a primary process in visuospatial memory while coordinate representation is a supplementary process. Moreover, neuroimaging results demonstrate bilateral activations when processing categorical or coordinate spatial judgments, which indicate that their underlying neural mechanisms may be similar.

Chapter 3. Development of the dot-cross task

3.1 Introduction

The experiments discussed in the previous chapter replicated a robust categorical advantage effect with the CATCOORD task, when stimuli are presented on the whole visual field. Importantly, while half visual field tasks demonstrate hemispheric lateralisation effects for categorical and coordinate spatial relations, the whole visual field 'CATCOORD' task also showed different performance for the two spatial changes in VSSTM. Specifically, categorical advantage effects have been consistently found in the CATCOORD task. The results support the notion that categorical spatial representations may be an intrinsic property of visuospatial representations. However, the anticipated lateralisation effects for the two spatial relations were not found in the neuroimaging study. Because this project aims to explore dissociable visuo-spatial processing and to observe possible scaffolding mechanisms in ageing, it is crucial to find a visual-spatial task that demonstrates clear lateralisation effects.

Kosslyn conducted a series of studies and showed hemispheric specialisation for categorical and coordinate spatial relations (Kosslyn, 1987). The results showed that responses were faster for judging whether a dot was on/off a blob (i.e. categorical spatial relations) when the stimuli were presented on the right visual field/left hemisphere, while responses were faster for judging whether a dot was near/far from a blob (i.e. coordinate spatial relations) if the stimuli were presented on the left visual field/right hemisphere. The observed hemispheric specialisation effects for the two spatial representations are thought to be a consequence of differences in processing speed between the two hemispheres. Jager & Postma (2003) reviewed studies of hemispheric specialisation effects for categorical and coordinate representations and the evidence supports the notion of a relative right hemisphere advantage in processing coordinate spatial relations and a left hemisphere advantage for categorical spatial relations. In addition, patients with an infarct in the left hemisphere were impaired on categorical judgments (e.g. object-location binding trials) whereas those with an infarct in the right hemisphere showed poor performance on coordinate judgments (e.g. position-only trials) (Kessels et al., 2002). The patients displayed impairments on performance of categorical and coordinate judgments, rather than inability to perform the task, suggesting that both hemispheres could process the two types of spatial relations but with different efficiency.

Whilst studies of categorical and coordinate spatial relations mostly address their characteristics of hemispheric lateralisation, some studies suggest that there may be continuity between the two types of spatial relations (Martin, Houssemand, Schiltz, Burnod, & Alexandre, 2008; Niebauer, 2001). More specifically, categorical spatial representations are thought to be an initial step in the formation of coordinate spatial representations. Niebauer (2001) adopted a prime paradigm to examine this hypothesis. Findings indicated that a prime with categorical information would speed up coordinate spatial judgments, yet a prime with coordinate information did not benefit categorical spatial judgments. Thus he suggests that categorical spatial representations may serve as an initial process for forming more precise coordinate spatial relations. A recent study with fMRI demonstrated that while both categorical and coordinate coding recruited the same fronto-parieto-occipital network for more general processes (e.g. visuo-spatial processing), coding of coordinate spatial relations also involved greater neural activity in dorsal-lateral prefrontal region, which is associated with attention and executive processes (Martin et al., 2008). Categorical spatial relations relied on an essential visual-spatial process, which indicates their initial role in VSSTM. Moreover, additional attention and executive neural networks were involved when more precise visual-spatial judgments were required, i.e. coordinate spatial relations. The neuroimaging evidence suggests that the two types of spatial relations are not independent processes but it is the different weighting of both processes that induces hemispheric specificity.

A well-studied half visual-field task, the ‘dot-cross’ task, is examined in this chapter. The task was developed by van der Ham and her colleagues and has demonstrated lateralisation effects for categorical and coordinate spatial relations in a series of studies (Ruotolo, van der Ham, Iachini, & Postma, 2011; van der Ham et al., 2012, 2009, 2010, 2007). In the original version of the dot-cross task, participants are informed of the type of spatial judgment required at the beginning of a trial with visual-verbal cues (e.g. categorical or coordinate). After that, the encoding image, which consists of a dot and a cross, is presented at the centre of the screen followed by a period of retention interval. Finally, the response image is shown on the left or right visual field. Hemispheric lateralisation effects have been demonstrated in both behavioural and neuroimaging studies (van der Ham et al., 2009, 2010, 2007). Participants showed better and faster performance for categorical spatial judgments when stimuli were presented on the right visual-field/left hemisphere while coordinate spatial judgments were performed better when the stimuli were presented on the left visual-field/right hemisphere. The original experiment design of providing spatial judgment cues prior to a trial may lead participants to encode a specific type of spatial relations and ignore the other spatial relations in the original design of the task. The current experiment design has made a few changes from the original task in order to closely examine the lateralisation effects for categorical and coordinate spatial representations. First of all, the timing of spatial judgement cues is delayed to later in the trials. Participants could not foresee types of spatial judgments and thus both categorical and coordinate spatial relations will be coded during the encoding stage. Secondly, the original visual-verbal cues (e.g. categorical and coordinate) are replaced with non-verbal tones (e.g. different pitches of beep) in order to avoid influences of verbal information on visual-spatial memory performance. These modifications minimise confounds from memory strategy development as well as verbal information. With these changes, the modified version of the dot-cross task is designed to examine the natural processing of categorical and coordinate spatial relations closely.

3.2 Experiment 3: Dot-cross task: A behavioural pilot experiment

3.2.1 Introduction

This experiment intends to explore the lateralisation hemispheric effects with the amended version of the dot-cross task. The modified version of the task is considered to be a stricter method of examining the hemispheric specialisation effects for the two spatial relations, since the types of spatial judgment cues are delayed and visual-verbal cues are changed to non-verbal tones. The delayed spatial judgment cues prohibit participants from encoding a specific type of spatial relationship. They will have to code both categorical and coordinate spatial relations during the encoding stage, which will increase memory loading in VSSTM capacity. The use of non-verbal tones increases the task difficulty by requiring participants to associate different pitches of tones to types of visual-spatial relations before making spatial judgments. It is hypothesised that hemispheric lateralisation effects will be revealed even in this more difficult experimental paradigm, compared to the original paradigm. According to previous findings (van der Ham et al., 2009, 2007), categorical spatial judgments are predicted to be processed faster when stimuli are presented on the right visual-field/left hemisphere (LH) while coordinate spatial judgments are predicted to be responded faster when stimuli are presented on the left visual-field.

3.2.2 Methods

3.2.2.1 Participants

Twelve healthy young students of Newcastle University were recruited (6 males and 6 females, mean age=22.8, *SD*=4.0). Participants had normal or corrected-to-normal vision and were all right-handed. All received a participation fee of £10 after they had completed the study. The research was approved by the Faculty of Medical Sciences Ethics Committee in Newcastle University.

3.2.2.2 Stimuli and design

The experiment stimuli followed exactly the same design as previous studies (van der Ham et al., 2009, 2010, 2007). Each encoding image and response image consisted of a black cross "+" and a single black dot "•" on a white background. Figure 3-1 shows all possible dot positions; ten in each quadrant of the cross, placed at four equally different distances from the centre of the cross. A small size of cross was adopted to reduce references which may aid categorical judgments and to minimise the difference in difficulty between categorical and coordinate trials (van der Ham et al., 2012).

The design of the dot-cross task was similar to the original version, aside from two modifications mentioned in previous section. The timing of the spatial judgment cues was delayed to just before the response image. Participants were given no clue to the type of spatial judgment that they would be expected to make during the encoding stage. The results would not be biased by knowing the types of spatial judgments in advance. Instead of visual-verbal cues ("quadrant" or "distance") being provided to instruct type of spatial judgment at the beginning of each trial, different pitches of sound were inserted just before responses: a low pitched beep (440Hz) indicated a categorical judgment (i.e. did the dot move to a different quadrant?) and a high pitched beep (1175Hz) indicated a coordinate judgment (i.e. is the distance between the dot and the cross the same?). Similar to the previous studies, the encoding stimuli were always placed at the centre of the screen and the response stimuli were presented at either left or right visual field (80 pixels away from the centre of the screen). The manipulation of the left- and right- visual field enables the lateralisation effects to be examined since they are projected onto right- and left-hemisphere, respectively.

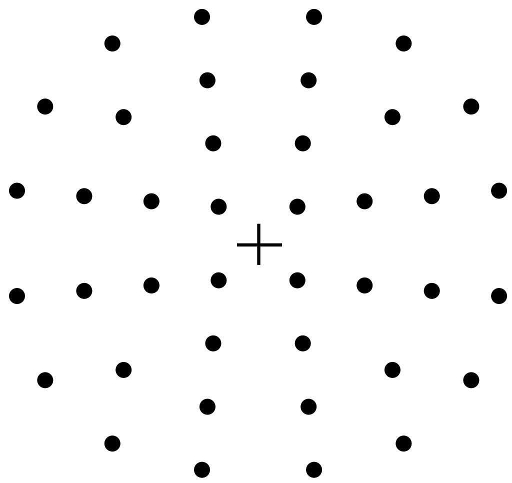


Figure 3-1. All possible dot positions in the stimuli design. There were four quadrants each containing 10 possible positions and 4 different distances between the dot and the centre of the cross. A 'match' response is given when the dots in the encoding and response images appear within the same quadrant (categorical judgment) or with the same distance (coordinate judgment) to the centre of the cross.

3.2.2.3 Procedure

Each participant was tested individually in a quiet room. The experiment was performed using Presentation® software (version 16.2, www.neurobs.com). Twenty practice trials were provided to participants with feedback to ensure that they understood the experiment procedure and the instructions. Participants then completed the formal experiment session. An experimental trial began with a fixation point "*" at the centre of the computer screen for 500ms. The encoding image was shown for 150ms, followed by a blank interval for

1500ms, and “×” was presented for 500ms accompanied by a beep. Finally, the response image was displayed for 150ms. Participants were asked to make a same/different judgment of the two successive images during the display of the response image (maximum 2000ms) (see Figure 3-2 for an illustration). Participants were instructed to utilise the index or middle fingers of their right hand to press the key “←”(same) or “→”(different) on the keyboard. The next trial started as soon as participants made a response. The formal experiment session consisted of five blocks with 65 trials in each block. Categorical and coordinate spatial judgments were completely randomised by the Presentation software. Both accuracy and reaction times were recorded.

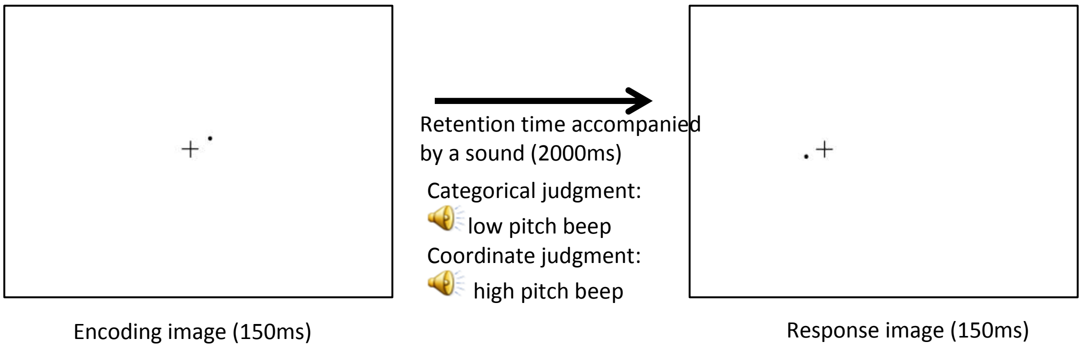


Figure 3-2. Example trial of the dot-cross task. In this example, if a low pitched beep was played, i.e. a categorical judgement was cued, then the correct response would be ‘different’, but if a high pitched beep was played, i.e. coordinate judgement, the correct response would be ‘same’.

3.2.2.4 Data analysis

Both accuracy and reaction times (RTs) were recorded for all trials. A 2 (spatial judgments: categorical vs. coordinate judgments) × 2 (hemispheres: left vs. right) within-subject repeated-measures analysis of variance (ANOVA) was performed on the accuracy and RTs. The main interest of the current experiment is the effect of the presentation visual fields/hemispheres on different spatial judgments. An interaction between types of spatial judgment and hemispheres is expected.

3.2.3 Results

Accuracy results showed that there was no significant interaction between spatial judgement and hemisphere (*F*<1) (see Figure 3-3). Similar performance for categorical and coordinate spatial judgments was found, regardless of the visual field in which the image was presented. Importantly, the categorical advantage effect was found ($F(1,11)=7.10$, $p=0.02$). This finding supports the previous experiments with the CATCOORD task and suggests a dominant role of categorical spatial representations in VSSTM. There was no significant difference between the left and the right hemisphere (*F*<1).

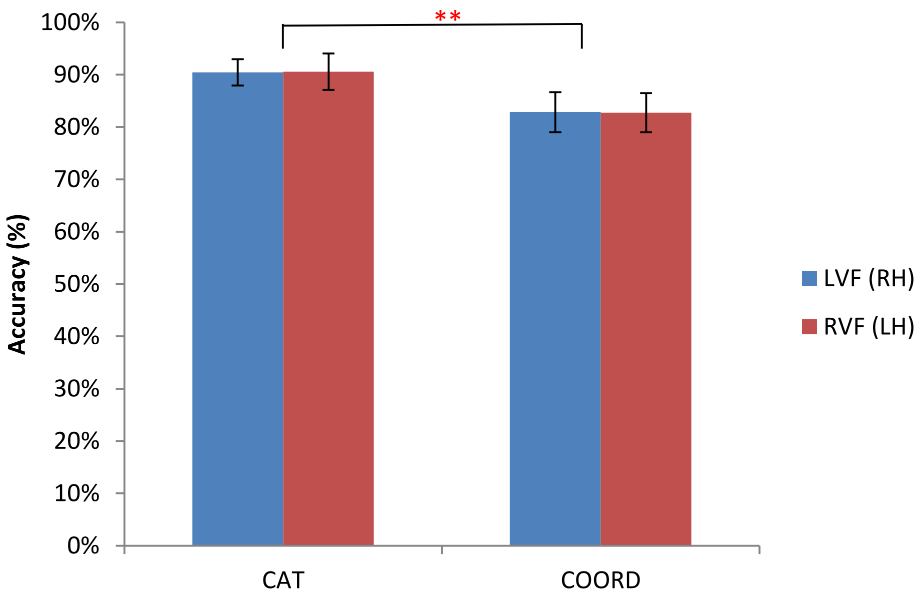


Figure 3-3. Mean accuracy for the dot-cross task. '**' indicates $p<0.01$.

Figure 3-4 illustrates the mean RTs. There was a significant interaction between the types of spatial judgement and the hemispheres ($F(1,11)=13.66$, $p=0.004$). Paired sample t-test indicated that for categorical judgments, responses were faster when stimuli was presented to the left hemisphere (LH) than the right hemisphere (RH) ($t(11)=-2.61$, $p=0.024$). For coordinate judgements there was a trend that participants responded quicker when stimuli were presented to the RH than the LH, though the difference was not significant ($t(11)=0.93$, $p=0.37$). There were no main effects on the spatial judgements ($F(1,11)=1.16$, $p=0.31$) and the hemispheres (*F*(1,11)=0.75, *p*=0.41). The interaction showed the hypothesised lateralisation effect for categorical spatial relations; they were processed faster in the left hemisphere than in the right hemisphere.

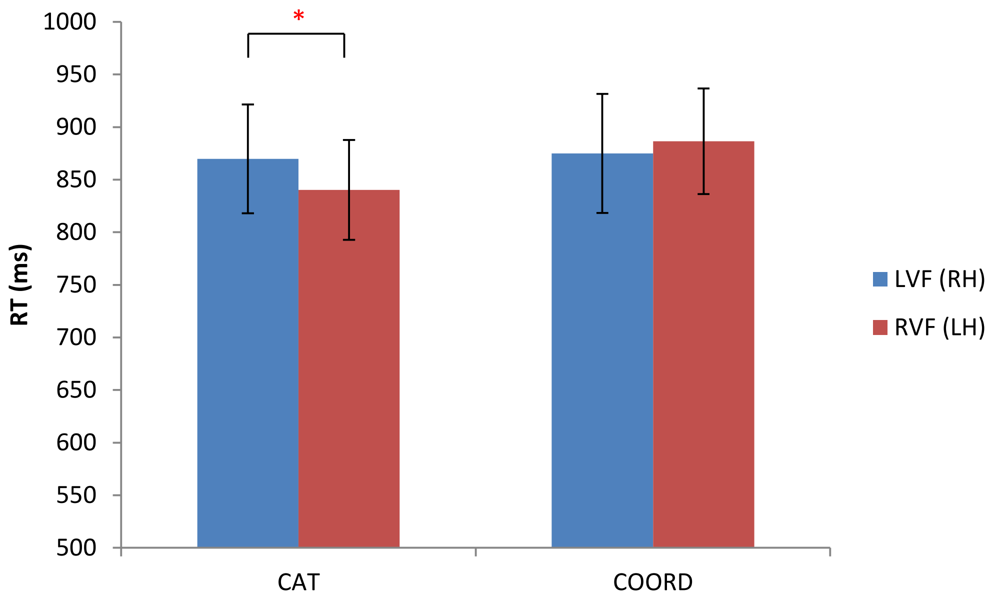


Figure 3-4. Mean reaction times for the dot-cross task. '*' indicates $p<0.05$.

3.2.4 Exploratory analyses

Figure 3-5 shows a split-half analysis for better understanding of the lateralisation effects observed in RT and to inform the design of an fMRI study. The analysis separated the trials into the first half trials vs. the last half trials. The results showed that an interaction between spatial judgments and hemispheres existed in the last half of the trials (*F*(1,11)=14.83, *p*=0.003) but not the first half (*F*<1). Paired sample t-tests suggested that the categorical processing was faster when stimuli were presented to the LH than the RH (*t*(11)=-2.72, *p*=0.020). More importantly, coordinate spatial judgments were faster when the stimuli were presented to the RH than the LH (*t*(11)=2.92, *p*=0.014). The main effect of spatial judgments was not significant in the first half (*F*<1) or the second half (*F*(1,11)=2.06, *p*=0.179) of the study. Similarly, there was no main effect of hemispheres in the first half (*F*(1,11)=1.32, *p*=0.275) and the second half (*F*<1) of the study. The results suggested that the lateralisation effects for categorical and coordinate spatial relations required practice to develop since they only occurred in the last half of the trials.

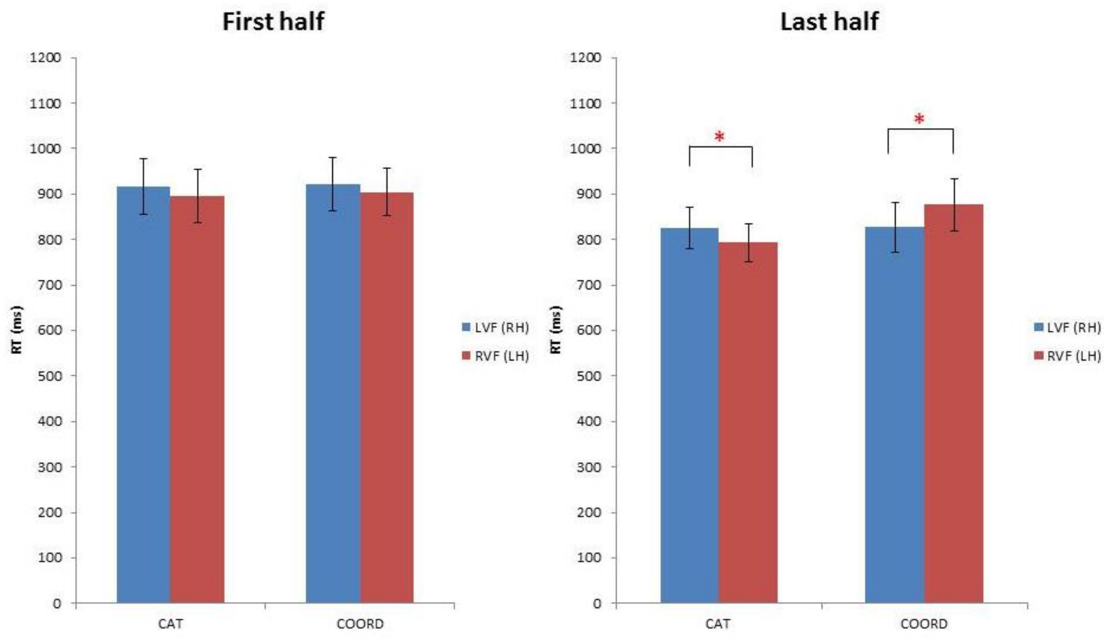


Figure 3-5. Mean RTs for the first and the last half of the study. '*' indicates $p<0.05$

As the interaction between spatial judgments and hemispheres only occurred in the latter part of the task, an additional analysis of task performance using cumulative trial selections was utilised to examine whether the two spatial representations are a continuum process in VSSTM. Figure 3-6 illustrates the performance of the two spatial relations in different hemispheres over time. The left hemisphere was consistently faster in processing categorical spatial relations whereas the right hemisphere advantage in processing coordinate spatial relations appeared gradually.

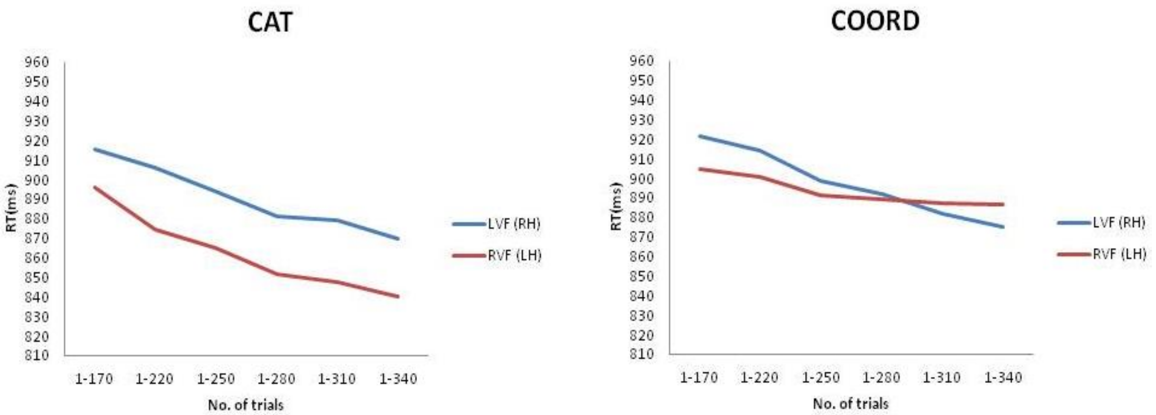


Figure 3-6. Mean RTs for categorical and coordinate spatial judgments throughout the study.

3.2.5 Summary and discussion of Experiment 3

The results have demonstrated hemispheric lateralisation effects in the modified version of the dot-cross task. While spatial judgment cues were delayed until retrieval and visual-verbal cues were replaced by non-verbal tones, minimising verbal influence and allowing encoding to occur without direction, the hemispheric specificity for processing the two spatial relations still occurred. Participants showed faster responses for categorical judgments when the stimuli were presented to the LH and coordinate spatial judgments were responded to faster if the stimuli were presented to the RH. More interestingly, the left hemisphere advantage for categorical processing appears all the time, whereas the right hemisphere advantage in processing coordinate spatial relations does not emerge until the later part of the experiment.

The fact that lateralisation effects emerged in reaction times but not accuracy suggested that categorical and coordinate spatial relations possess different processing speeds: the left hemisphere is much more “efficient” (for the same accuracy of performance, the response times are quicker) in processing categorical spatial relations while the right hemisphere is more efficient in processing coordinate spatial relations (Jager & Postma, 2003; Kosslyn et al. 1989; Kosslyn et al., 1998; Palermo et al., 2008; Postma et al., 2008; van der Ham et al., 2007; van der Ham et al., 2009). The exploratory analysis indicated that the lateralisation effects did not occur until later in the study. The results demonstrated that the advantage of the LH in processing categorical spatial relations existed at the beginning of the experiment whereas the RH advantage for processing coordinate spatial relations emerged much later. It is possible that coordinate spatial relations recruit additional attentional and executive processes, which require more time/practice before they can be detected in VSSTM (Martin et al., 2008). More importantly, the current result demonstrates a continuum of visuospatial process between categorical and coordinate spatial relations, which is consistent with previous findings (Niebauer, 2001; Martin et al., 2008).

Hemispheric lateralisation effects have been replicated with the dot-cross task, which examined the two spatial relations more strictly. The following experiment is designed to investigate the underlying neural mechanism of categorical and coordinate spatial processing on the same task. The behavioural and neuroimaging results will help to inform the design of studies for subsequent middle-aged and older populations.

3.3 Experiment 4: Dot-cross neuroimaging study

3.3.1 Introduction

The modified version of the dot-cross task has demonstrated lateralisation effects in the previous study. van der Ham et al. (2009) showed hemispheric lateralisation effects with the dot-cross task in parietal-occipital regions in an fMRI study. In their study, participants were instructed with types of judgments before they encoded the stimuli and they would carry out the same spatial judgment for a number of trials (i.e. a block design). The present experiment utilised an event-related design with the modified dot-cross task to investigate the underlying mechanism when processing the two spatial representations. The hypothesis is that lateralisation effects will be observed in the fMRI study. It is predicted that greater neural activities will be observed in the left parietal-occipital area when processing categorical judgments and greater activations in the right hemisphere when processing coordinate judgments.

3.3.2 Methods

3.3.2.1 Participants

Twenty healthy young participants who had not participated in Experiment 3 were recruited to the fMRI study. Ten females and 10 males completed the study. However, two of the participants had to be excluded from the analysis due to extremely poor performance in accuracy (outside of 3SD) or excessive head movements (> 3mm). Overall 9 females (mean age=28.67, SD=3.12) and 9 males (mean age=26.67, SD=6.04) were included in the final analysis. All participants were right-handed and had normal or corrected-to-normal vision. Participants received £20 after they had completed the neuroimaging study. The research was approved by the Faculty of Medical Sciences Ethics Committee in Newcastle University.

3.3.2.2 Experiment material, design and procedure

The stimuli and design were identical to Experiment 3. An event-related design was created for the fMRI study where participants could not predict types of spatial judgments until they heard the beeps. Presentation® software, (version 16.2, www.neurobs.com) was utilised to execute the task. Before entering the scanner, participants underwent 176 practice trials outside of the scanner to familiarise them with the task. According to the exploratory analysis in the previous experiment, it is known that the interaction appeared in later trials of the task. The practice session would hopefully to maximise hemispheric lateralisation effects for the later part of the trials, which were performed in the scanner. The stimuli were projected onto a rear-projection screen via a pico projector located at the head of the scanner and were visible via an overhead mirror. Participants were asked to indicate a "same" or "different" judgement via an MRI-compatible button box upon presentation of response image using the index or middle finger of their right hand. A pair of MRI-compatible headphones was applied so that participants could hear the different pitch sounds. Fifty practice trials were provided to participants during the anatomical scan in order to acclimatise them to the experimental procedure and mode of response. During the scan session, another 176 trials were provided to participants, with a 10 second break (resting state) between each 8 trials. The duration of the scan session was 21 minutes. Both accuracy and reaction times were recorded via Presentation software.

3.3.2.3 Data analysis

3.3.2.3.1 Behavioural data

Both accuracy and reaction times (RTs) were recorded for all trials of the dot-cross task. Only the trials that were performed in the scanner, i.e. the later part of the task, were analysed. A 2 (spatial judgments: categorical vs. coordinate judgments) × 2 (hemispheres: left vs. right) within-subject repeated-measures analysis of variance (ANOVA) was performed on the accuracy and RTs.

3.3.2.3.2 Imaging data

Images were acquired on a 3-Tesla Philips Intera Achevia MRI system. For functional scans a single-shot EPI sequence was used and MR acquisition parameters were as follows: TE=30ms; TR=2600ms; FOV (right-left, anterior-posterior, and foot-head)=200*200*140 mm; flip angle=650; voxel size=3×3×3.5mm^3. T1-weighted structural images were acquired before functional scans began. Image processing and statistical analysis were performed with SPM8 software (www.fil.ion.ucl.ac.uk). The images underwent slice-time correction firstly during pre-processing to account for differences in slice acquisition. After that, realignment and unwarping processing were carried out to remove artefacts from within images. Co-registered images were then applied to the first scan of the block followed by normalisation. Normalisation steps registered unwarped images to a standard MNI template before images underwent smoothing with an 8mm full-width half-maximum Gaussian kernel. This minimised the effect of differences in neuroanatomy between subjects.

First-level analysis applied a general linear model to estimate the related BOLD responses across four conditions, separated into correctly and incorrectly answered trials: categorical trials, coordinate trials, LH/right visual-field trials and RH/left visual-field trials. The high-pass filter was set at 128s to reduce low-frequency noise. Movement parameters were included in the model to reduce movement related artefacts.

A flexible factorial design was applied in a second-level statistical analysis; only scans for correct answered trials were included in the analysis. Cluster activations, relative to activity at fixation baseline, in the “categorical” and “coordinate” conditions were deemed significant if a $p<0.05$ (Family-Wise Error correction) was achieved. Similarly, contrast images were created to compare activity in the categorical and coordinate conditions; significance was determined if $p<0.05$ (FWE correction). The WFU PickAtlas toolbox for SPM8 was used to identify activated cluster area.

3.3.3 Results

3.3.3.1 Behavioural results

Accuracy of performance is depicted in Figure 3-7. Similar to Experiment 3, a main effect of spatial judgments was found in the scanner ($F(1,17)=5.31$, $p=0.034$). Categorical spatial judgments were performed better than coordinate spatial judgments. However, the main effect of hemispheres was not significant ($F<1$). Interaction between spatial judgments and hemispheres was not found either ($F<1$). Spatial judgments were not affected by the visual field in which the stimuli were presented. Categorical spatial representation always showed better performance than coordinate spatial representation.

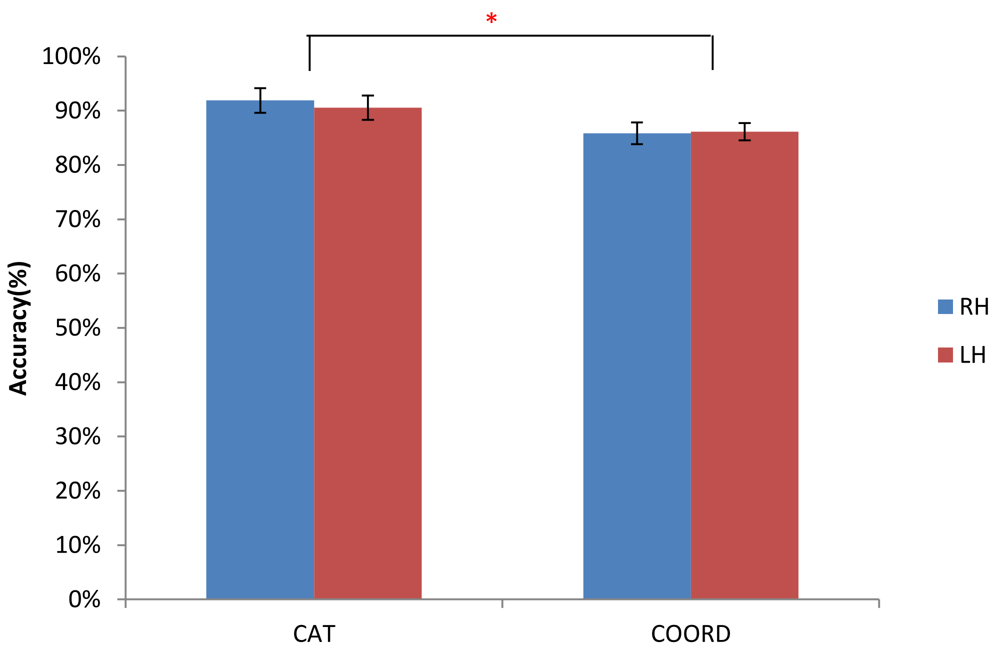


Figure 3-7. Mean accuracy for the dot-cross fMRI study. '*' indicates $p<0.05$.

Figure 3-8 shows means of reaction times. The main effects of spatial judgments and hemispheres were not significant (Fs<1). Importantly, the interaction between spatial judgments and hemispheres was significant ($F(1,17)=5.41$, $p=0.033$). Post hoc analysis indicated that categorical spatial judgments showed faster response time than coordinate spatial judgments when stimuli were presented in the LH ($t(17)=-2.21$, $p=0.041$). A strong trend towards a significant effect for coordinate spatial judgments was found ($t(17)=2.02$, $p=0.059$). Participants made faster coordinate responses if stimuli were presented in the RH than the LH. Hemispheric lateralisation effects were shown by the LH advantage in processing categorical spatial relations. Overall, the behavioural results have replicated the findings from Experiment 3 and suggest that reaction time is a better index than accuracy to illustrate hemispheric specificity for categorical and coordinate spatial relations.

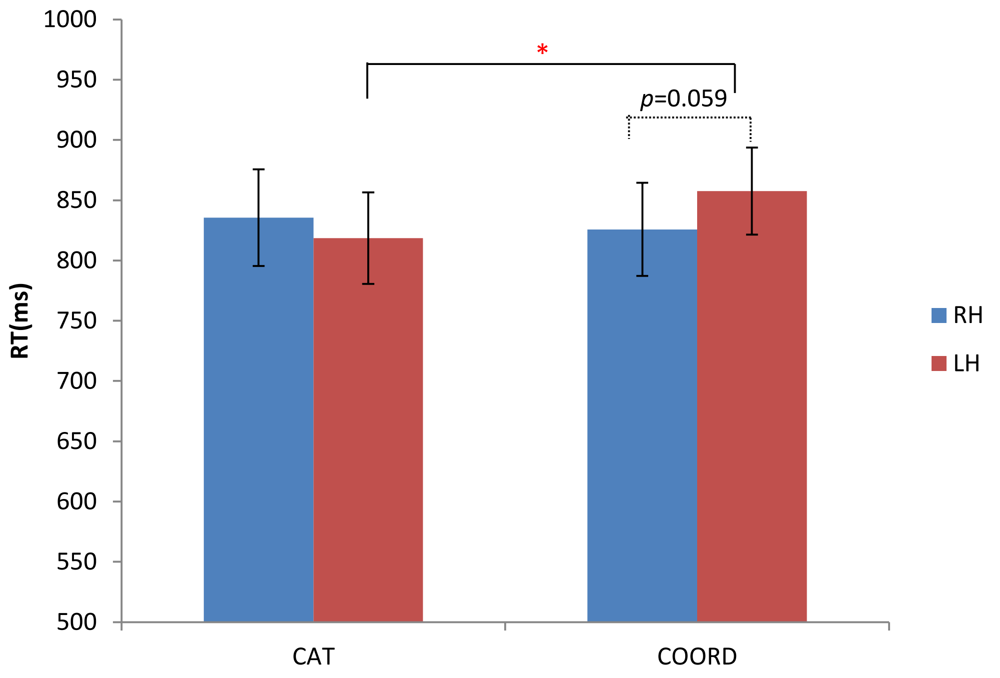


Figure 3-8. Mean reaction times for the dot-cross fMRI study. '*' indicates p<0.05.

3.3.3.2 Neuroimaging results

The voxel-based comparisons for categorical vs. resting state and coordinate vs. resting state are presented in Figure 3-9 ($p<0.05$ after FWE correction). Similar to the neuroimaging result with the CATCOORD task, bilateral brain activation was found when processing categorical and coordinate spatial judgments in the dot-cross task. The results suggested that the two spatial representations may share similar neural networks. The manipulated half visual-field presentation of stimuli did not affect the spatial processing.

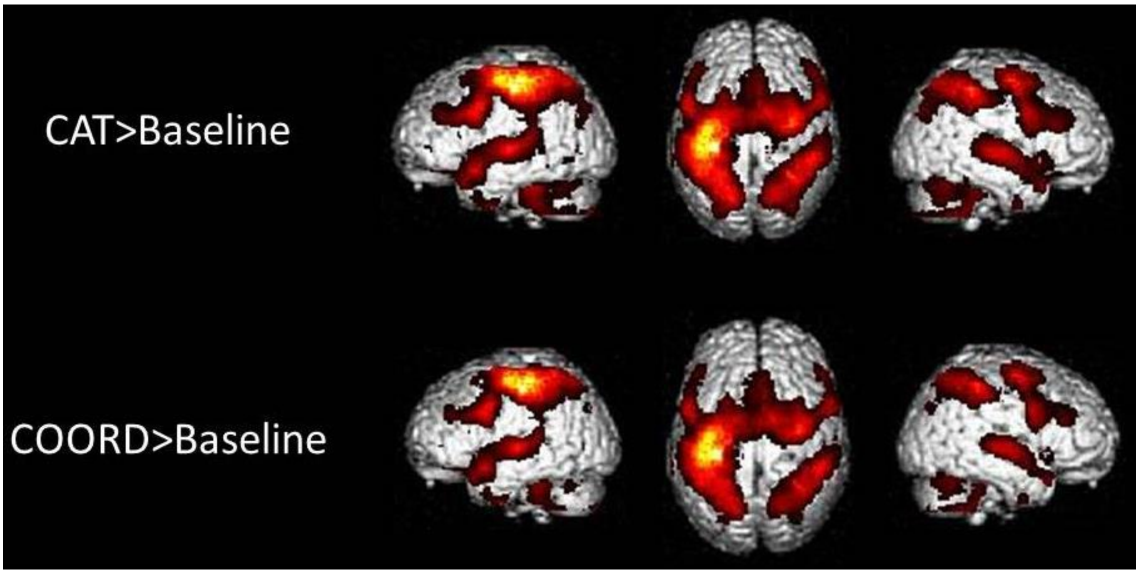


Figure 3-9. Contrasts of categorical or coordinate conditions vs. baseline (FWE correction, $p<0.05$).

In order to compare different brain regions involved in categorical and coordinate spatial judgments, signals acquired during the response phase in the categorical condition were contrasted with the coordinate condition (CAT>COORD). Note that the response phase comprises the duration between the end of stimuli presentation and the response button being pressed. The categorical condition showed greater BOLD signal changes than the coordinate condition in parietal-temporal regions, including right middle-temporal gyrus, right superior temporal gyrus, left inferior parietal lobule, and right middle frontal gyrus. Precuneus and superior parietal region showed bilateral activation (see Figure 3-10 and Table 3-1). However, none of the brain regions showed greater activations when processing coordinate spatial judgments than categorical spatial judgments. The results showed greater neural activation when processing categorical than coordinate spatial relations.

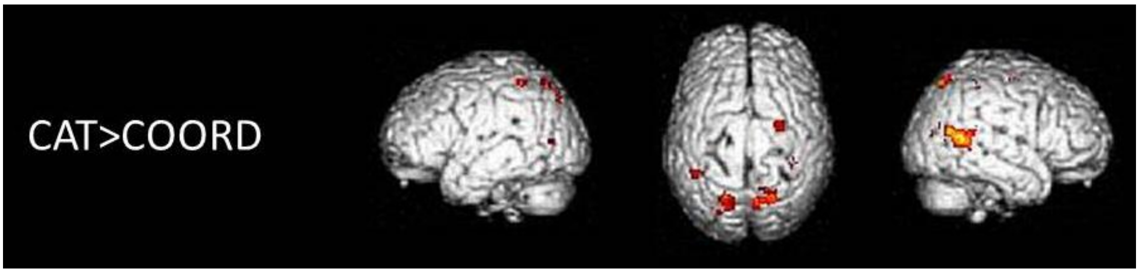


Figure 3-10. Contrast of the categorical>coordinate condition (FWE correction, $p<0.05$).
N.B. There were no significant clusters found in the reverse contrast (COORD>CAT).

Table 3-1. Top clusters for the whole brain analysis for the CAT>COORD contrast (FWE correction, $p<0.05$, $k\geq10$).

Region	Local peak	Cluster (voxels)	*t*-value (peak)	Mean Z (peak)	MNI mm (x,y,z)
Temporal	R middle temporal gyrus	357	6.80	5.71	(58,-52,6)
	R superior temporal gyrus		6.71	5.65	(48,-60,16)
Parietal	R superior parietal lobule	143	6.14	5.29	(20,-68,54)
	R precuneus		6.08	5.25	(8,-70,50)
	L precuneus	89	5.90	5.13	(-16,-74,50)
	L superior parietal lobule		5.86	5.10	(-16,-66,54)
	L inferior parietal lobule	30	6.04	5.22	(-44,-46,58)
	L precuneus	11	5.80	5.06	(-22,-78,42)
Frontal	R middle frontal gyrus	50	6.64	5.61	(58,-52,6)

The reverse contrast for task difference (COORD>CAT) showed no significant clusters.

3.3.4 Exploratory analysis

As demonstrated in the previous experiment, reaction times are able to identify hemispheric lateralisation effects, and are therefore thought to be a better indicator of hemispheric specificity. The current analysis utilised reaction time as a modulator to explore changes of BOLD signals for trials with longer reaction times. It is assumed that these represented more difficult trials. Therefore, the observed regions, which showed greater BOLD signal changes, would represent areas that were involved when processing more difficult trials. The results showed that greater BOLD signal changes were observed in bilateral frontal regions when processing coordinate spatial judgments but not categorical judgments. Because frontal regions are associated with attention and central executive ability, it is thought that participants involved these cognitive functions to process finely detailed coordinate spatial relations (see Figure 3-11 and Table 3-2).

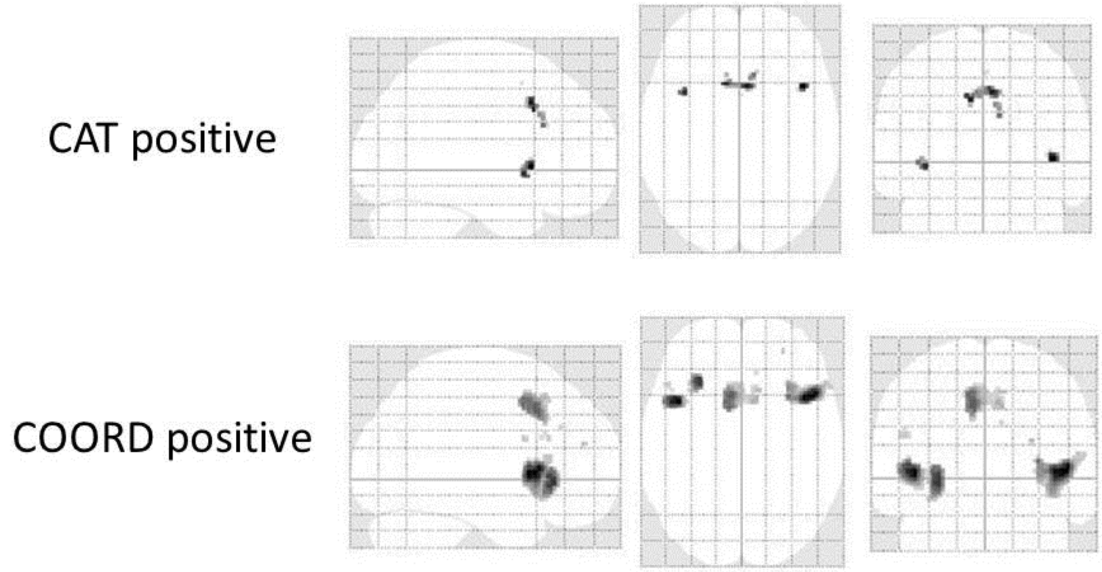


Figure 3-11. Glass brain images represent the associated brain activation with longer reaction time (FWE correction, *p*<0.05, *k*≥10).

Table 3-2. Top clusters for the whole brain analysis for categorical and coordinate spatial processing (FWE correction, *p*<0.05, *k*≥10).

Region	Local peak	Cluster (voxels)	*t*-value (peak)	Mean Z (peak)	MNI mm (x,y,z)
		Categorical positive activations			
Sub-lobar	R insula	15	6.09	5.25	(44,16,2)
	L insula	13	5.90	5.13	(-36,12,-2)
Limbic lobe	R cingulate gyrus	39	5.96	5.17	(6,16,42)
	L cingulate gyrus		5.94	5.15	(-8,18,38)
		Coordinate positive activations			
Frontal	R inferior frontal gyrus	383	8.16	6.49	(48,18,4)
	R insula		6.71	5.66	(32,18,10)
	L inferior frontal gyrus	147	7.36	6.05	(-28,30,-2)
	L insula	175	7.97	6.39	(-42,14,4)
Limbic lobe	L cingulate gyrus	255	6.93	5.79	(-6,18,44)
	R cingulate gyrus		5.95	5.16	(8,14,44)

3.3.5 Summary and discussion of Experiment 4

Experiment 4 has replicated the behavioural results of Experiment 3 by demonstrating the hemispheric lateralisation effects in reaction times. More importantly, the neuroimaging results showed bilateral activation when processing categorical and coordinate spatial judgments, which were consistent with the previous findings from the CATCOORD task. Categorical and coordinate spatial representations share similar neural networks in visuospatial representations. In addition, the exploratory results showed greater BOLD signal changes in frontal regions when processing difficult coordinate spatial judgments but not categorical spatial relations.

The current study adopted an analysis utilising reaction times as modulator to explore the neuroimaging results. Participants showed greater BOLD signal changes in inferior frontal regions when processing coordinate but not categorical judgments. There is broad agreement in literature that executive functions are associated with prefrontal activations (Alvarez & Emory, 2006; Kane & Engle, 2002; Miller, 2000). Hampshire et al. utilised an attention relevant task, a stop signal task, to examine the role of the right inferior frontal gyrus (Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010). The results showed right inferior frontal gyrus activation when the stop signal cue was detected. Similarly, greater BOLD signal changes in bilateral inferior frontal gyrus in the present experiment suggests that while processing spatial changes with similar difficulty, participants recruited more attention resources to process fine grain coordinate spatial representations. The results exhibited a difference in activation regions between categorical and coordinate spatial processing instead of hemispheric lateralisation effects. Coordinate spatial representations are considered by participants to be difficult hence they apply regions that are associated with attention and executive function to process them.

The fact that the hemispheric lateralisation effect was not found in the neuroimaging data may also be due to fewer experimental trials being carried out inside the scanner. According to the findings in Experiment 3, hemispheric specificity requires time to develop and emerges in later trials. Although participants underwent practice trials, which were designed to maximise lateralisation effects in the scanner, the effects were not observed in a later section of the task. The fact that the practice trials did not help to develop lateralisation effects in later trials may be due to changes of experiment environment, which may eliminate practice effects for categorical and coordinate spatial judgments.

To conclude, Experiment 4 supports the previous finding by demonstrating behavioural lateralisation effects in reaction times with the modified dot-cross task. Importantly, with fMRI, consistent bilateral activations were found in both the CATCOORD task and the dot-cross task, indicating that categorical and coordinate spatial representations may share similar neural networks in VSSTM. Moreover, only coordinate spatial representation was seen to recruit attention and executive functions to process more difficult trials. Even though hemispheric lateralisation effects were not demonstrated in the current fMRI study, the results illustrate the difference between the two spatial representations by revealing neural activations in different brain regions.

3.4 Summary of Chapter 3

In the present chapter a modified dot-cross task was introduced to observe lateralisation hemispheric effects for categorical and coordinate spatial representations. The modified version of the dot-cross task was designed to examine the two spatial representations closely by delaying spatial judgment cues and eliminating visual-verbal intrusion. The behavioural hemispheric lateralisation effects for categorical and coordinate spatial representations were still observed even with these changes. The neuroimaging results revealed bilateral activations when processing either categorical or coordinate spatial judgments, which supports the findings of the CATCOORD task. The consistent finding of bilateral activation for categorical and coordinate spatial relations suggests that both spatial relations share similar neural mechanisms. In addition, while the advantage of the left hemisphere in processing categorical spatial representations is spontaneous, the right hemisphere requires time/practice to develop its efficiency in processing coordinate spatial representations. The neuroimaging results support the behavioral results by depicting activation in frontal region while processing difficult coordinate spatial judgments but not categorical spatial judgments. The finding indicates that the dot-cross task is a suitable task to investigate scaffolding mechanisms and a pattern of scaffolding networks is not restricted to left and right hemisphere recruitments. More attention engagements or applying a cognitive strategy may also be a form of scaffolding mechanisms (Park & Reuter-Lorenz, 2009).

This chapter aimed to find a visual-spatial task that reveals lateralisation effects to explore further in ageing. With the modified version of the dot-cross task, the behavioural results showed hemispheric specificity for categorical and coordinate spatial process in reaction times. However, the neuroimaging data did not support van der Ham's findings of lateralisation effects when participants are aware of types of spatial judgments in advance. The bilateral activations observed in Experiment 4 suggest that previous findings of lateralised activations for categorical and coordinate spatial relations may have been caused by the specific methodologies used. Moreover, a difference in brain activation regions between categorical and coordinate spatial processing was observed when processing difficult trials. Only coordinate spatial processing involved greater BOLD signal changes in inferior frontal regions, which are associated with attention and executive functions process.

Since the current paradigm has demonstrated lateralisation effects for categorical and coordinate spatial representations in reaction times, the next step will be to apply the paradigm to older adults. The next experiment will investigate the neural network pattern of the healthy ageing brain when processing the task. Specifically, older adults with better and poorer cognitive ability may adopt different memory/neural mechanism strategies to process the dot-cross task.

Chapter 4. Neuropsychological functions and Ageing

4.1 Introduction

Chapter 2 and Chapter 3 were designed to explore categorical and coordinate visuo-spatial processing with different experiment tasks with young participants. The dot-cross task showed lateralisation effects behaviourally, and more importantly, the neuroimaging results revealed a form of cognitive scaffolding; participants recruited attention and executive resources when performing difficult coordinate trials but not categorical trials. This chapter will investigate neuropsychological performance with middle-aged and older adults and neural networks in older adults when performing the dot-cross task. Exploratory analyses will be carried out to explore possible different cognitive profiles and neural networks between participants with better and poorer cognitive ability.

Cognitive ability declines with ageing. However, not all cognitive abilities show the same speed of decline. Specifically, verbal ability shows relatively steady performance across lifespan whereas spatial ability and central executive functions show a powerful influence of age (Park, Polk, Mikels, Taylor, & Marshuetz, 2001). Several theories have been suggested for the different speeds of decline in various cognitive abilities. The HAROLD theory suggests that cognitive ability shows different speeds of decline in different hemispheres, whereas the right-hemi aging hypothesis states that the right-hemisphere related functions are more likely to be affected by age than those associated with the left hemisphere (Brown & Jaffe, 1975; Cabeza et al., 2002; Cabeza, 2002; Dolcos et al., 2002). However, neither theory can account for why some old adults show better cognitive performance than others. Park and Reuter-Lorenz (2009) proposed the scaffolding theory of ageing and cognition (STAC), which suggests that in old adults who show good cognitive performance, it is because of their efficient usage of additional cognitive resources to 'scaffold' their degenerating functions. For example, participants showing successful cognitive scaffolding may exhibit bilateral activation, specifically in the prefrontal areas (Cabeza & Dennis, 2012; Cabeza et al., 1997; Cabeza et al., 2002; Reuter-Lorenz, Stanczak, & Miller, 1999; Reuter-Lorenz et al., 2000) or a shift from posterior to anterior activations (Davis et al., 2008; Dennis & Cabeza, 2008). The dedifferentiation hypothesis holds a different opinion in interpreting the broad neural network (i.e. more brain regions are involved in cognitive processing) found in the ageing brain. It suggests that the diverse neural activity is caused by decrease in neural specificity (Hedden & Gabrieli, 2004; Park et al., 2004; Reuter-Lorenz & Park, 2010), increased noise in neural transmission (Li, Lindenberger, & Sikström, 2001; Li & Sikström, 2002; Persson et al., 2006) or increased neural plasticity to 'repair' the declined function (Erickson et al., 2007; Greenwood, 2007; Mishra, Rolle, & Gazzaley, 2015; Raz & Lindenberger, 2013) resulting in poor cognitive performance in older adults. Whether the broad brain activity is the result of compensation or an intrusion from increased noise in the ageing brain is still under debate.

As mentioned in the previous chapter, the hemispheric lateralisation of categorical and coordinate spatial processes has been demonstrated in previous studies (Kessels, Kappelle, de Haan, & Postma, 2002; Kosslyn et al., 1989; Kosslyn, 1998; Postma, Kessels, van Asselen, & Asselen, 2008; 2010; van der Ham, Raemaekers, van Wezel, Oleksiak, & Postma, 2009) as well as in Experiment 3 & 4. The current study utilises the characteristic of lateralisation of the two spatial processes to further our understanding of cognitive scaffolding. The aim of Experiment 5 is to utilise a broad neuropsychological test battery to separate the participants into higher- and lower-performance groups and further to correlate their cognitive performance with their performance on the tasks of interest, i.e. the CATCOORD task and the dot-cross task. A neuroimaging study (Experiment 6) is also included to attempt to understand the underlying mechanism of spatial ability in age-related cognitive decline. To further examine the ageing hypotheses, comparisons of the cognitive profiles as well as the brain networks of the higher- and lower-performance groups are performed. Cabeza and colleagues (2002) utilised a right-lateralised source memory task to investigate different neural networks between the young, old-high and old-low group. The results showed that the old-low group utilised similar lateralised activation as the young group, whereas the old-high group showed bilateral activation when performing the task. The findings support the HAROLD hypothesis in which cognitive ability shows different decline rates in different hemispheres. Importantly, older adults exhibiting bilateral activation showed better performance on the task than those who exhibited unilateral activation. The additional contralateral activation observed in the old-high group is suggested to be a scaffolding strategy in order to maintain declined right-hemisphere related cognitive ability. The hypothesis for the current study is that older adults with better and poorer cognitive ability will exhibit different cognitive profiles and neural networks when performing cognitive tasks.

If the STAC is supported, it is anticipated that the higher-performance group will recruit additional cognitive resources (e.g. verbal information or attention resources etc.) to 'scaffold' their declined visuo-spatial ability and/or the lateralisation effects of the spatial relations would be less pronounced. However, if the lower-performance group shows broader brain network in the imaging study and/or less distinct hemispheric effects, then the dedifferentiation hypothesis is supported.

4.2 Experiment 5: Neuropsychological study of healthy middle-aged and older people

4.2.1 Introduction

The purpose of this experiment is to understand how aging affects people's cognitive performance and, more importantly, how people deal with cognitive decline. A neuropsychological battery was introduced to measure general cognitive ability among the participants and to examine the relationship between different cognitive functions. In order to examine possible compensatory mechanisms for visuo-spatial ability, the CATCOORD task and the dot-cross task were included to explore the effects of healthy ageing on the two types of spatial relations. Two different age range groups, middle-aged and old groups, were included. In addition, comparisons of higher and lower cognitive performance groups in the neuropsychological battery were performed in order to inspect possible scaffolding networks in older people.

4.2.2 Methods

4.2.2.1 Participants

Twenty healthy middle-aged participants (age range between 45 and 59, 10 males and 10 females, mean age=52.15, *SD*=4.4) were recruited in the middle-aged group. Fifty-one healthy older participants (aged range between 60 and 94, 21 males and 30 females, mean age= 68.51, *SD*=8.3) were recruited in the old group. Participants were recruited from Newcastle Institute of Neuroscience participant pool, regional community clubs, Newcastle City council, Age UK, and Elders Council of Newcastle. Participants received £20 after they had completed the study. The research was approved by the Faculty of Medical Sciences Ethics Committee at Newcastle University.

General inclusion and exclusion criteria are presented below:

Table 4-1. Inclusion and exclusion criteria for the middle-aged and old-age participants

Inclusion criteria	Exclusion criteria

• Age criteria
  ○ Middle-age (45-59 years old)
  ○ Old age (age above 60 years old)
• Normal or corrected to normal vision
• Right handed (as assessed Edinburgh Handedness Inventory)
	• History of neurological or psychiatric illness
	• Currently taking any medication or had a medical condition that could affect cerebral blood flow (e.g. high blood pressure).
	• Current drug dependence or alcohol misuse (only accepted into the study if their current alcohol intake was less than 28 units per week for men and 21 units per week for women.)
	• History of head injury with loss of consciousness exceeding 5 minutes
	• Diagnosed amnesia or dementia
	• Any other significant, uncorrected physical or neurological illness

4.2.2.2 Design of the neuropsychological battery

The participant information sheet and a consent form were presented to participants before the study. Once participants agreed to undertake the study, a demographic information sheet was presented for participants to complete. The NART (Nelson, 1982) was then administrated to estimate the premorbid verbal IQ followed by a series of neuropsychological tests. The neuropsychological battery was designed to test several broader cognitive domains. The cognitive abilities related to each test are provided in the following table.

Table 4-2. Neuropsychological battery.

Task	Related cognitive domain
1. NART	Estimate verbal IQ
2. Trail Making Test (Part A)	Psychomotor speed
3. Trail Making Test (Part B)	Executive function
4. Digit symbol substitution Test (DSST)	Psychomotor speed
5. Dot-Cross Task	Visuo-spatial ability
6. Rey-AVLT (immediate recall)	Verbal ability
7. CATCOORD Task	Visuo-spatial ability
8. Rey-AVLT (delayed recall and recognition)	Verbal ability
9. Digit Forward Span	Verbal working memory
10. Digit Backward Span	Executive function
11. Stroop	Executive function
12. Object Relocation Task	Visuo-spatial ability
13. Visual Pattern Test (VPT)	Visuo-spatial ability
14. Serial Spatial Span (SSP) (CANTAB)	Visuo-spatial ability
15. Line-Bisection Task	Hemispheric related task

Numbers represent order of administration. Computerised tasks are shaded.

4.2.2.3 Procedure

Participants were sat in a quiet room for about 2 hours to complete the neuropsychological assessment, with breaks between the tasks. The neuropsychological battery was designed to assess general cognitive abilities via both pen-and-paper tests and computerised tests. Detailed descriptions of each task and details of their administration are presented below.

4.2.2.4 General screening test

4.2.2.4.1 National Adult Reading Test (NART)

The NART was originally designed to estimate premorbid intelligence levels for patients with intellectual deterioration (Nelson, 1982).The test presents 50 English words which do not follow the phoneme-orthography rules, e.g. '*CHORD*'. The predicted verbal IQ follows the NART manual, and is derived from the number of errors, i.e. words which participants do not recognise and pronounce incorrectly. The correct pronunciations of the 50 words were written on the experimenter's manual in International Phonetic Alphabet (IPA) based on the Oxford English Dictionary online (http://www.oed.com/).

Participants were encouraged to read all of the words without any time limitation.

Table 4-3. National Adult Reading Test (NART) word list.

CHORD	COURTEOUS	HIATUS	FAÇADE	GAUCHE
ACHE	RAREFY	SUBTLE	ZEALOT	TOPIARY
DEPOT	EQUIVOCAL	PROCREATE	DRACHM	LEVIATHAN
AISLE	NAÏVE	GIST	AEON	BEATIFY
BOUQUET	CATACOMB	GOUGE	PLACEBO	PRELATE
PSALM	GAOLED	SUPERFLUOUS	ABSTEMIOUS	SIDEREAL
CAPON	THYME	SIMILE	DÉTENTE	DEMESNE
DENY	HEIR	BANAL	IDYLL	SYNCOPE
NAUSEA	RADIX	QUADRUPED	PUERPERAL	LABILE
DEBT	ASSIGNATE	CELLIST	AVER	CAMPANILE

4.2.2.5 Primary spatial tests

4.2.2.5.1 CATCOORD task

The task procedure was similar to the paradigm introduced in Exp.1a with young people. In order to fit the task alongside other neuropsychological tests, participants only underwent 72 trials: Twenty-four categorical change trials, 24 coordinate change trials with two shift sizes (20mm and 25mm), and 24 same/no-change trials. A visual array consisted of four to-be-remembered squares presented on an image of the same colour, red. The manipulation aimed to minimise characteristics of stimuli and to force participants to encode as much spatial information as possible for the presented image. The to-be-remembered image was presented for 2500ms encoding time followed by a blank maintenance interval for 2000ms, and then the response image was shown until the response was made or up to 4000ms. The response time was extended for older participants because of their potentially slower motor responses. Participants were instructed to use their left index finger to press 'z' if they found that the four squares were located at the exact same positions between the encoding image and the response image. If any of the squares was detected to have changed position, they were required to press 'm' by using the right index finger. Participants were informed that both accuracy and response time were equally important.

4.2.2.5.2 Dot-Cross task

The paradigm was exactly the same as Exp. 3 with the young group, apart from the number of trials which was reduced to 200 for older people. Additionally, response time was extended to 3000ms. The duration of stimuli presentation was identical to that in Exp. 3. The encoding image was presented for 150ms followed by a maintenance interval for 2000ms. The response image appeared, and then disappeared after 150ms presentation. Participants were asked to indicate their responses using the index ('same') and middle ('different') fingers of their right hand. They were also reminded to respond as quickly and accurately as possible.

4.2.2.6 Secondary neuropsychological battery

4.2.2.6.1 Psychomotor tests

4.2.2.6.1.1 Trail making test part A

This part of the Trail making task contained one practice trial and one experimental trial. In the practice trial, the numbers '1' to '8' were presented at random locations in an array. Participants were asked to draw a line to join the numbers sequentially, from the beginning '1' to the end '8', without lifting the pen from the paper. Time was critical in this task; participants were instructed to draw the line as quickly as possible. Time to completion was recorded. The procedure was the same in the experimental trial, but the presented digits were increased to 25.

4.2.2.6.1.2 Digit Symbol Substitution Test (DSST)

This task included 4 sections: the original version, the number version, symbol copy, and error check. In the original version, a reference row of 9 digits paired with 9 symbols was presented on top of the sheet. A row of digits was randomly provided underneath the reference row. Participants were required to copy the correct symbols underneath the digits in accordance with the presented reference row. The number version was similar to the original version, but required participants to copy the appropriate numbers below the presented symbols in reference to the row on top of the sheet. The symbol copy requires participants to copy a row of symbols directly into a row below it. The error check presents numbers and symbols to the participants and requires them to find the incorrectly copied symbols according to the reference row on top of the sheet. Within all sections, 8 practice samples and 93 real trials were included and participants were instructed to copy the symbols/numbers/check errors in order. Participants were given 90 seconds to complete as many trials as they could.

4.2.2.6.2 Attention and executive function tests

4.2.2.6.2.1 Trail making part B

This part was similar to part A of the Trail making test (4.2.2.6.1.1). The only difference is that not only numbers but also alphabetic letters were included in this part. Participants were required to draw a continuous line joining through each character, in the order of number ('1') –letter ('A') –number ('2') –letter ('B') and so on. Time to completion was recorded.

4.2.2.6.2.2 Stroop

The Stroop task used here has three parts: 1) Word list: Participants were presented with a number of words and required to read the words out loud as quickly as possible. 2) Coloured XXX list: 'XXX' were presented in three different colours (red, blue, and green), and participants were asked to read out the colours. 3) Conflict list: three colour words ('red', 'green', and 'blue') were shown printed in different colours (red, green, and blue) to create conflict. For example, if ‘blue’ was presented to participants, they were required to read out the ink colour ‘red’ instead of the word itself. Time to completion was recorded as well as errors.

4.2.2.6.2.3 Digit Span (backward)

The experimenter read out a series of numbers (length from 2 to 7 digit numbers) and required participants to repeat the numbers in reverse order. Each series of numbers had two trials and was stopped if participants failed twice to report the correct reversed order.

4.2.2.6.3 Verbal ability tests

4.2.2.6.3.1 Rey Auditory-Verbal Learning Test (Rey-AVLT)

Rey-AVLT consists of 5 parts to examine participants’ verbal memory abilities, including short-term, long-term memory, and recognition. In the first part of the test, the experimenter read out list A 5 times and asked participants to recall the words each time. In the second part, participants heard a different word list, list B, and were required to recall the words. Participants were then asked to recall the words in list A. The fourth section examined the retention ability; participants were occupied with a completely different task, the CATCOORD task, for 20 minutes and then were required to recall list A again. Finally, the experimenter read out a set of words which contained words from list A, list B, or which did not appear in any list. Participants were asked to say whether a word was from list A, list B, or no list. Recognition ability for word lists was examined.

4.2.2.6.3.2 Digit Span (forward)

Similar to Digit Span (backward) (4.2.2.6.2.3), the experimenter read out a series of numbers (length from 3 to 8 items) and asked participants to read them back in the same order. Each series had two trials and the task was stopped if participants failed to recall the correct order twice.

4.2.2.6.4 Spatial ability tests

4.2.2.6.4.1 Visual Pattern Test (VPT)

A series of grids consisting of black and white squares were presented. Participants were asked to memorise the pattern of shaded squares. Once the grid disappeared from the computer screen, participants were required to shade in the squares on a score sheet in the same pattern as they had seen previously.

1(2)

Figure 4-1. An example of a VPT trial.

4.2.2.6.4.2 Spatial Span (SSP) (a CANTAB test)

This task assesses participants' visuospatial working memory capacity. An array of white boxes was presented on the screen, some of which changed colour in sequence. Participants were required to memorise the sequence and make responses in the same order on a touch-screen monitor after the computer presentation. The number of boxes increased from two at the beginning of the test to nine at the end. The sequence and colour varied throughout the test, but only one colour was shown in each sequence. The program ended automatically if participants failed to recall the sequence correctly three times within the same spatial span.

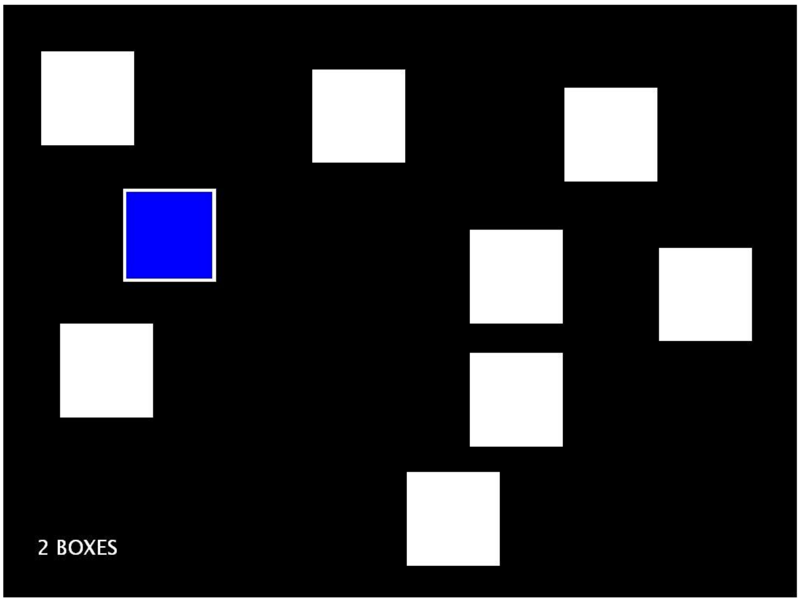


Figure 4-2. An example of a spatial span trial.

4.2.2.6.4.3 Object Relocation Task (ORT)

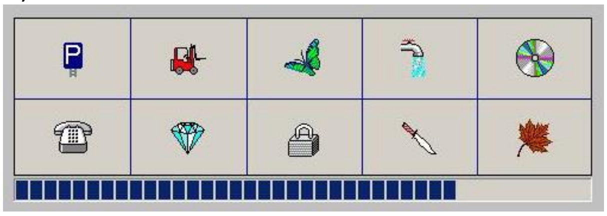
The Object Relocation Task was first introduced by Kessels, Postma, & de Haan (1999). The programme runs under Windows system with a touch-screen monitor. Different parameters can be manipulated to examine various domains of spatial memory. A number of studies have utilised the task to study different populations including patients (Gallagher, Gray, & Kessels, 2014; Kessels, Postma, Kappelle, & de Haan, 2000; Postma, Kessels, van Asselen, & Asselen, 2008) and older adults (Kessels, Hobbel, & Postma, 2007; Meulenbroek et al., 2010).

The program version utilised in this experiment was identical to Gallagher et al. (2014)'s design. The program was divided into 5 subsections with 1 practice trial (containing 4 objects/positions) and 2 experimental trials (containing 10 objects/positions) for each subsection. The first two subsections (object memory test and visual spatial reconstruction test) are categorised as control conditions and the latter three subsections (position-only memory, object-location binding, and combined memory test) examine the abilities of immediate recall and recognition of objects and their positions.

i. Object Memory (OM)

This first part of the task examines participants' object identity memory. Participants were given 20 seconds to remember 10 different objects. After that, they were asked to identify the 10 presented objects out of 20 objects (with 10 distracters). No time limit was applied during the response phase.

A)



B)

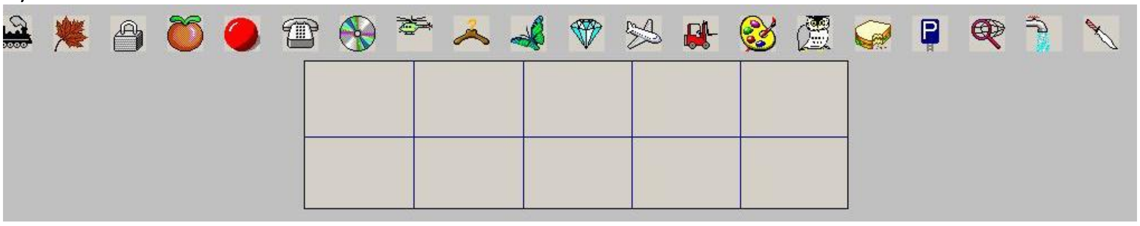


Figure 4-3. Object memory test. A) Stimuli image: The bottom bar represents timing. B) Response image.

ii. Visuospatial Reconstruction (VSR)

Participants were presented with an array of 10 different objects located at different positions on the left of the screen. On the right of the screen, a blank box was presented along with the same objects displayed on top of the box. Participants were instructed to place the objects into the blank box in an arrangement that was exactly the same as the one to the left.

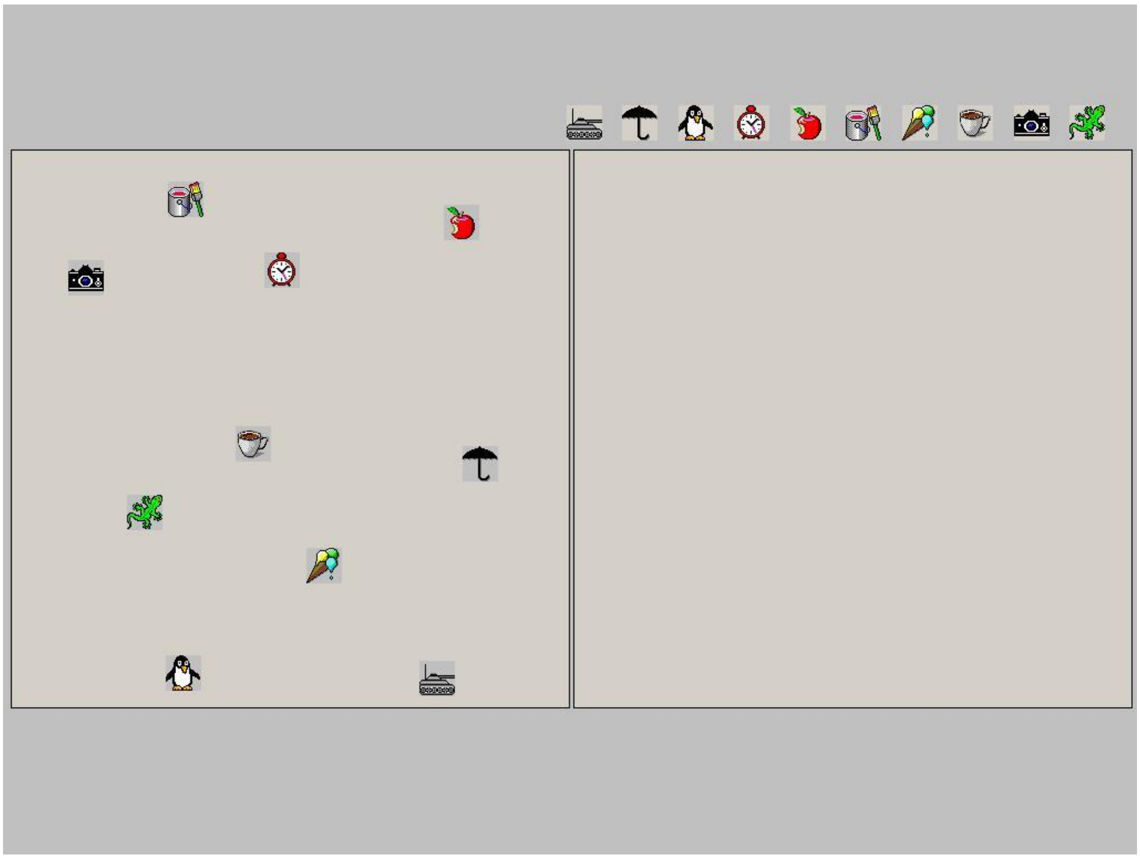


Figure 4-4. Visuo-spatial reconstruction task.

iii. Position-only Memory (POM)

An array containing 10 identical objects was presented. Participants were instructed to memorise their exact positions. The array disappeared after 20 seconds. During the recall phase, a blank array along with the same objects displayed on top was shown to participants. They were required to move the objects into the empty box and place them onto the exact remembered positions as closely as possible.

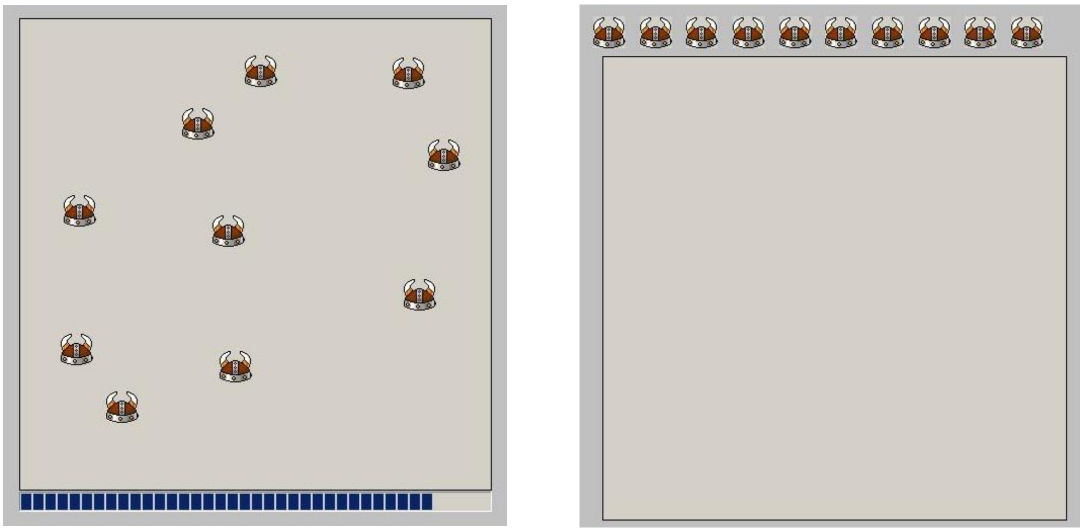


Figure 4-5. Position-only memory task. The left image is the stimuli image and the right image is the response image.

iv. Object-location Binding (OLB)

Participants viewed an array of 10 different objects for 20 seconds. They were required to remember where the objects were located. After that, the array disappeared and the objects were presented on the top of the screen. 10 black dots were also presented within the box to indicate the locations of the objects. Participants were then required to relocate the objects onto their correct positions. Percentage of errors was recorded.

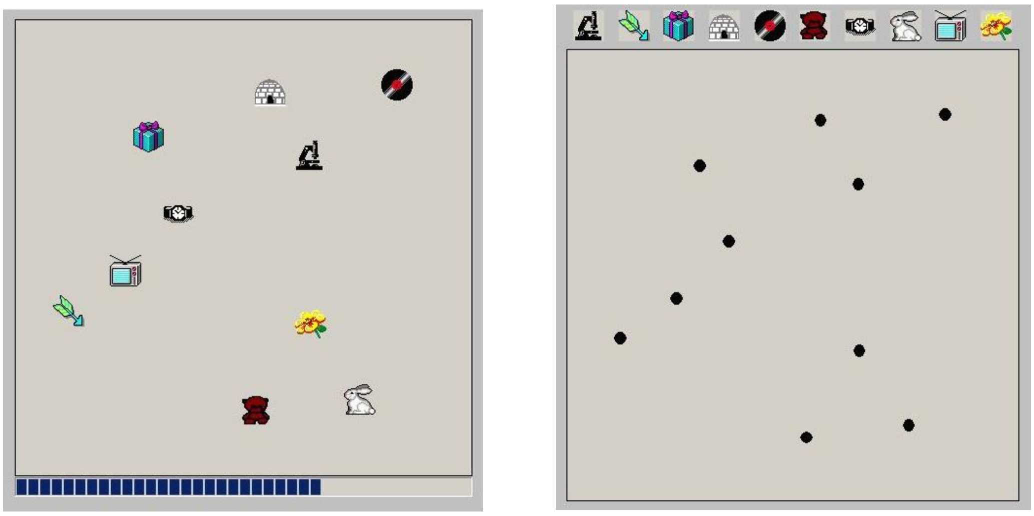


Figure 4-6. Object-location binding task. The left represents the stimuli image and the right represents the response image.

v. Combined memory (COM)

The final task was identical to the OLB condition apart from removing the additional position hints during the recall phase. Participants were required to allocate correct objects onto exact positions in the blank array without the black dots as support. The difference between the original object location and participants' allocated location were recorded in millimetres.

Figure 4-7. Combined memory task. The left image is the stimuli and the right image is the response image.

4.2.2.6.5 Hemispheric relevant test: the Line-Bisection Task (LBT)

The line-bisection task was designed by Hausmann (2005) and has demonstrated its sensitivity in showing the effect of hemispheric asymmetry of spatial attention between genders. Specifically, males are biased to the left while females are biased to the right when dividing the lines. The line-bisection task consists of 17 horizontal black lines of 1mm width on white A4 paper. The lines ranged from 10cm to 26cm in length with a 1cm interval between each line and the next. The position of the lines (left, centre, or right) was pseudorandomly presented since it showed important influence on the results. Seven lines appeared in the middle of the sheet, five lines appeared near the left margin and five lines near the right margin, which was 13mm away from the edge. The lengths for the centred lines were 1cm × 12cm, 2cm × 18cm, 2cm × 22cm, and 2cm × 24cm. The left- and right-lateralised lines were 1cm × 10cm, 2cm × 14cm, 2cm × 16cm, and 2cm × 20cm (see Figure 4-8 for an illustration). Participants were instructed to draw a midpoint, which segments the lines into two parts of equal length, with the pen in one hand first and then repeated with the other. Participants were instructed to scan each line from left-to-right or right-to left by placing the pen at the end of the line, moving the pen along the line until they thought the centre of the line had been reached, and then setting the mark. The order of the two scan-direction conditions was counterbalanced. A line was covered after it was marked to ensure that the participants were not biased by their previous judgments. There was no time restriction. The deviations to the left or to the right of each marked line were carefully measured to 0.1cm accuracy. The pen deviation score for each line was computed as ((measured left half – true half)/true half) × 100. The mean score for all lines was computed separately for each hand used under each condition. Negative values indicate a left bias and positive values indicate a right bias.

With inclusion of this task in the neuropsychological battery, the hemispheric effect of the dot-cross task would be observed for participants who were not eligible for the neuroimaging study.

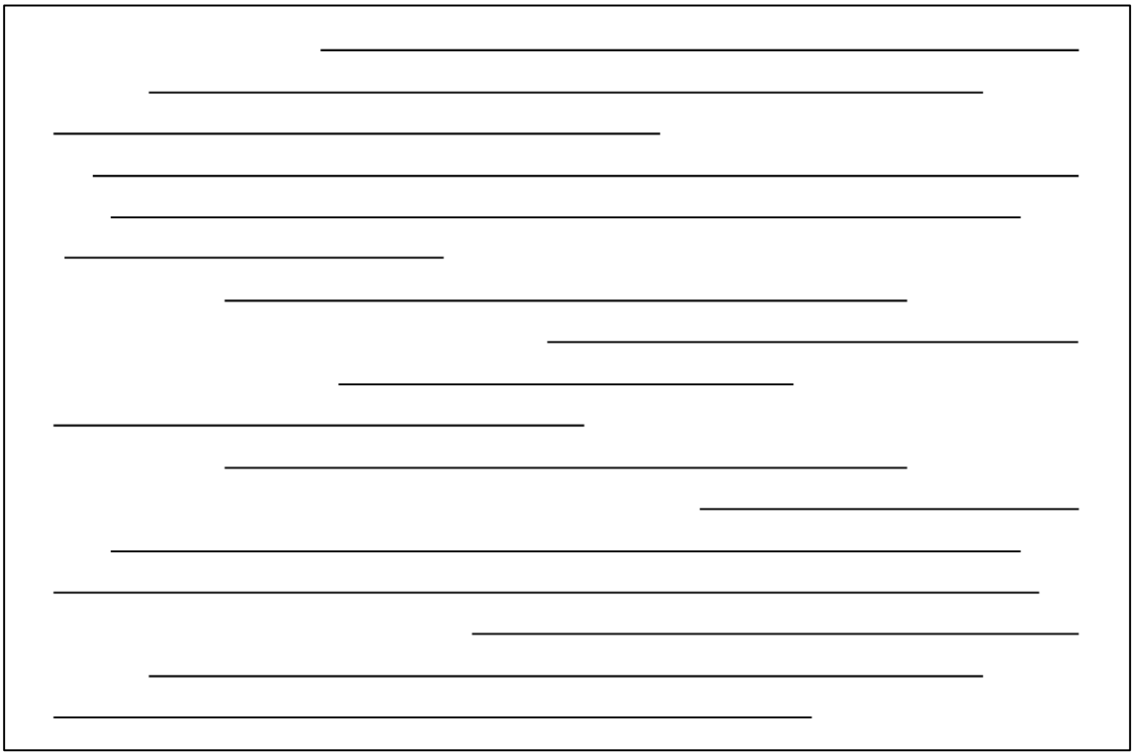


Figure 4-8. Line-bisection task.

4.2.2.7 *Data analysis*

For the primary spatial tasks, repeated measure ANOVA was applied for both accuracy and reaction times for the middle-aged and old groups. The CATCOORD task included data from 20 middle-aged participants and 51 older participants. For the dot-cross task, all 20 middle-aged participants were included in the analysis. However, one older participant was unable to complete the task and another 2 showed extremely poor performance (outside of 3 standard deviations from the mean), hence only 48 older subjects were included in the final analysis.

For the neuropsychological analysis, preliminary analyses were applied to understand the performance between the two age groups. The results were analysed with the raw data. The trail making test was recorded in seconds using a stopwatch. Stroop test was also recorded in seconds and the Stroop score was calculated via the following formula: (word list + coloured list)/2-conflict list. DSST, Digit Span (both forward and backward), Rey-AVLT, VPT, and SSP were recorded in number of correctly recalled/recognised items. Although DSST contained 4 subtests, the cognitive abilities they underpinned were highly correlated to each other. Therefore, only the original version was used for the result analysis. Similarly, only 3 of the Rey-AVLT subtests are included in the data analysis: A1 to A5 (learning ability), A7 minus A5 (delayed recall ability) and recognition of A1 list (recognition ability). The object relocation task was recorded in either distance (mm): VSR, POM, and COM, or percentage of errors: OLB and OM. The line-bisection task was recorded in centimetres.

An exploratory analysis was utilised to observe whether the neuropsychological profile differs between the higher- and lower-performance groups. In order to separate the higher- and lower-performance groups, all raw data of the neuropsychological tasks (excluding the line-bisection task (LBT)) were firstly transformed into Z scores. The Z score provides a standardised score for each task thus enabling further exploration. For the tasks which record in reaction times (e.g. Trail making test and Stroop), error rates (e.g. ORT:OLB), and distances away from the correct response (e.g. ORT:POM and ORT:COM), their Z scores were reversed so that a higher z score means better performance. After the transformation of the raw data, older participants were divided into higher- and lower-performance groups based upon their averaged Z score. Participants with Z score higher than the median were categorised into the higher-performance group, those lower than the median into the lower-performance group. Bivariate correlation was utilised to explore the relationship between different cognitive tasks in the higher- and lower-performance groups. Additionally, principal component analysis (PCA) was utilised to generate several cognitive domains. PCA extracts the common factors onto which the different tests and processes load to observe the relationship between various cognitive abilities without intrusion of artificial factors. Finally, linear regression was applied to observe components that contribute to the differences between the higher- and the lower-performance group the most.

4.2.3 Results

4.2.3.1 Tasks of interest

4.2.3.1.1 CATCOORD task

Compared to the results for young people (ref. Exp.1a), the results of middle-aged and older participants showed similar patterns. Figure 4-9 shows the accuracy of the three conditions, categorical, coordinate, and the same condition, for the middle-aged and old groups. The results indicated that there was a significant difference between the three types of trials (i.e., categorical-change trials, coordinate-change trials, and the same trials) in the middle-aged participants ($F(2,38)=15.93$, $p<0.001$). Specifically, the same condition was performed significantly better than the coordinate change trials ($t(19)=5.04$, $p<0.001$) and the categorical condition was performed better than the coordinate condition ($t(19)=3.67$, $p=0.002$). The same condition was performed slightly better than the categorical condition (at a trend level) ($t(19)=2.07$, $p=0.052$). Similarly, the main effect of the conditions was found in older adults ($F(2,100)=40.91$, $p<0.001$). The same condition was performed the best. Accuracy was significantly higher than the categorical change condition ($t(50)=5.44$, $p<0.001$) and the coordinate change trials ($t(50)=8.03$, $p<0.001$). In addition, the categorical condition was performed better than the coordinate change trials ($t(50)=3.98$, $p<0.001$). The effect of age group was significant ($F(1,69)=5.29$, $p=0.024$). Post hoc analysis indicated that the only difference between middle-age and older participants occurred in the categorical change trials ($t(69)=2.52$, $p=0.014$) but not in the coordinate change trials ($t(69)=1.68$, $p=0.99$) or the same trials ($t(69)=0.32$, $p=0.749$). Middle-aged participants performed significantly better on judging categorical changes than older participants. A main effect of the conditions remained ($F(2,138)=40.14$, $p<0.001$) but no interaction between the conditions and the groups ($F(2,138)=1.76$, $p=0.176$) was found.

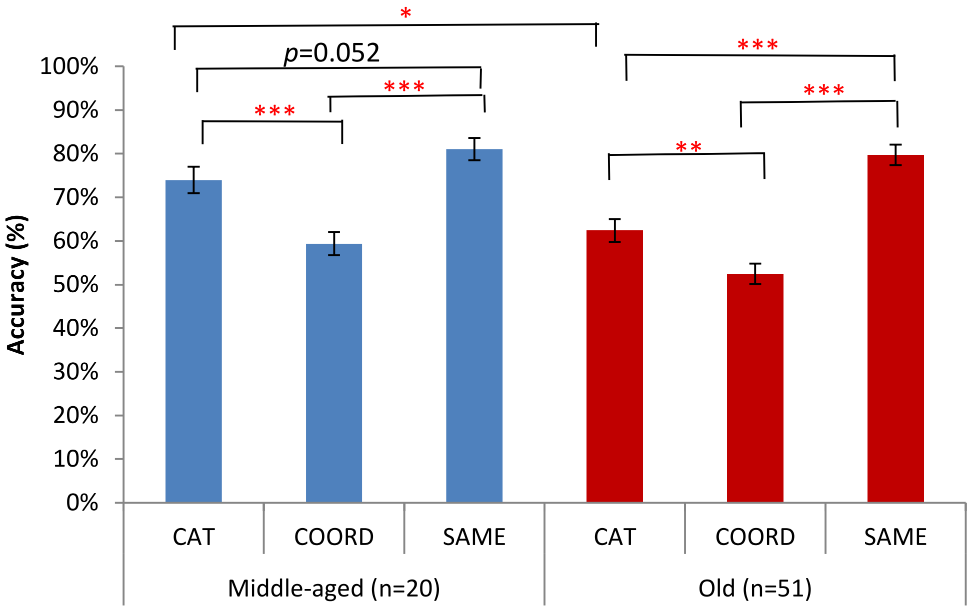


Figure 4-9. Accuracy for the categorical, coordinate, and the same condition for middle-aged and old participants in the CATCOORD task. '*' indicates $p<0.05$; '**' indicates $p<0.01$; '***' indicates $p<0.005$.

The results for reaction time are shown in Figure 4-10. The middle-aged group did not differ in responding to the three conditions ($F(2,38)=2.39$, $p=0.105$.), and nor did the older group ($F<1$.). There was no significant difference in responding to the three conditions. Both middle-aged and older participants took roughly the same amount of time in responding to categorical change, coordinate change, and the same trials. There was no group difference between middle-aged and older participants ($F<1$).

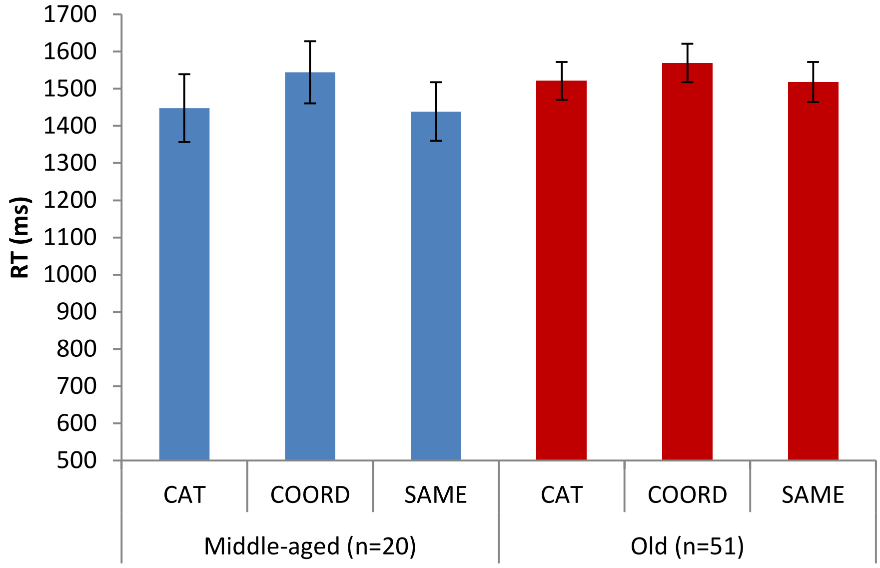


Figure 4-10. Reaction times for the categorical-changed, coordinate-changed, and the same condition for the middle-aged and the old participants in the CATCOORD task.

Figure 4-11 shows the accuracy for the categorical and coordinate spatial relations with either 20mm or 25mm shift for the middle-aged and older group. The same trials were excluded in this analysis as they included no shifts. A 2 (categorical vs. coordinate change trials) x 2 (20mm vs. 25mm) ANOVA was performed. Middle-aged participants showed significant main effects of the spatial relations ($F(1,19)=13.49$, $p=0.002$) and the shift sizes ($F(1,19)=35.77$, $p<0.001$). The results indicate that the categorical change trials were performed significantly better than the coordinate change trials. The greater the shift size, the easier it was to detect the positional change, resulting in better performance. Moreover, an interaction between spatial relations and shift sizes was found ($F(1,19)=13.21$, $p=0.002$). Post hoc analysis indicated that the largest shift size (25mm) was performed better than the small shift size (20mm) for the coordinate change trials ($t(19)=8.31$, $p<0.001$). In addition, participants were more accurate in the categorical change condition than the coordinate change in the small shift ($t(19)=5.08$, p<0.001). In the older group, the main effects of spatial relations ($F(1,50)=15.86$, $p<0.001$) and shift sizes ($F(1,50)=83.77$, $p<0.001$) were found as well. Similarly to the middle-aged group, the older adults showed better performance in detecting categorical change than coordinate change. In addition, participants detected the positional differences for targets better in the bigger shift size trials. The interaction between spatial relations and shift sizes was also significant ($F(1,50)=25.76$, $p<0.001$). Post hoc analysis showed that memory performance was better in the largest shift than the small shift trials for the categorical change condition ($t(50)=2.62$, $p=0.012$) and the coordinate change condition ($t(50)=9.23$, $p<0.001$). Moreover, when the shift size was small (20mm), participants memorised better for categorical representations than coordinate representations ($t(50)=5.22$, $p<0.001$). In addition, there was significantly different performance between the middle-aged and the older group ($F(1,69)=6.33$, $p=0.014$). The middle-aged group showed much better performance than the older group when the spatial change was categorical and the target had been shifted by 25mm ($t(69)=2.69$, $p=0.009$).

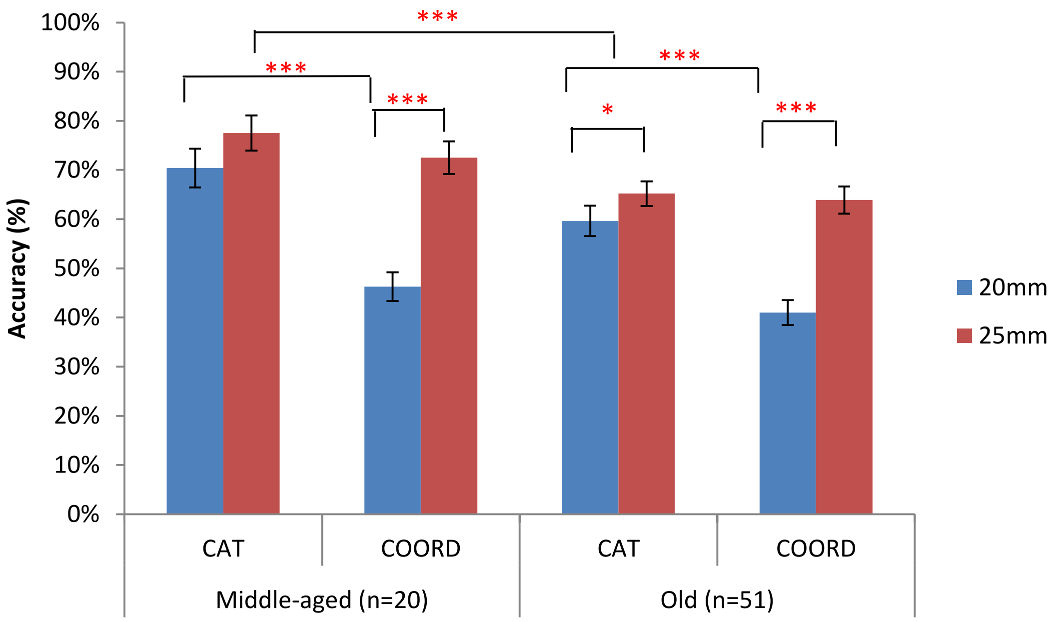


Figure 4-11. Accuracy of the categorical- and coordinate-changed condition with different shift sizes (20mm vs. 25mm) for middle-aged and older participants in the CATCOORD task. '*' indicates $p<0.05$; '***' indicates $p<0.005$.

Figure 4-12 displays the reaction times for the two spatial relations and the two shift sizes for the middle-aged and the old groups. Middle-aged participants showed significantly faster responses in detecting categorical change trials than the coordinate change trials ($F(1,19)=5.12$, $p=0.036$). However, the different shift size did not affect the response speed ($F(1,19)=1.30$, $p=0.268$), nor did the interaction between the spatial relations and the shift sizes ($F<1$). The main effects of the spatial relations and the shift sizes were not significant in the older group ($F(1,50)=1.67$, $p=0.203$ and $F(1,50)=2.27$, $p=0.138$); older subjects responded to the trials similarly regardless of the types of spatial change and the sizes of target shift. In addition, there was no interaction between the spatial relations and the shift sizes ($F<1$). The manipulation of spatial relations and shift sizes did not affect response time in the older group. There was no significant difference in the comparison of middle-aged and older groups, with participants in both groups showing similar response time (F<1).

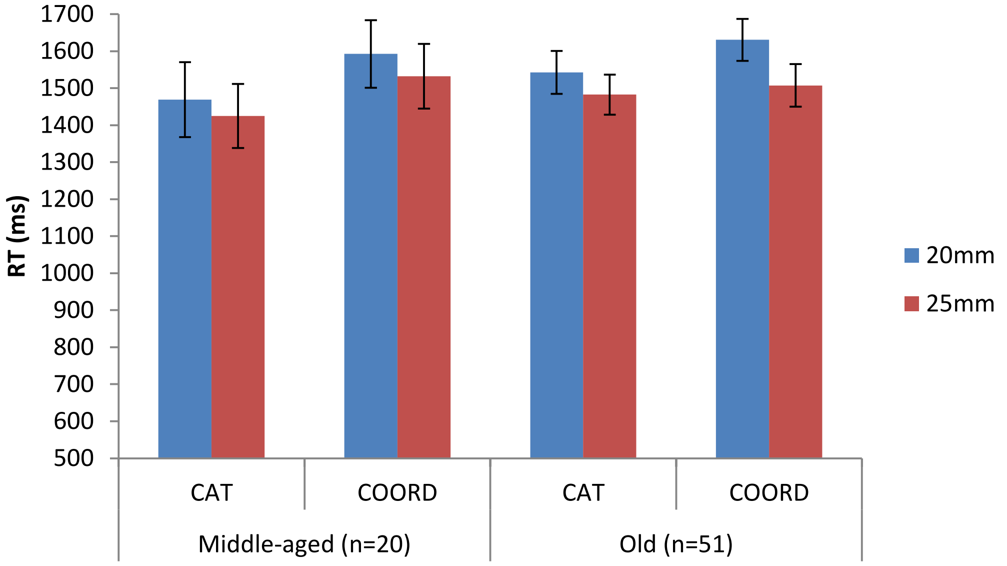


Figure 4-12. Reaction times for the categorical- and coordinate-changed condition with different shift sizes (20mm vs. 25mm) between middle-aged and old participants in the CATCOORD task.

In sum, the categorical advantage effect was consistently found in both the middle-aged and the older group. Bigger shift size leads to better memory performance. The sensitivity of coordinate spatial relations to distance changes has been observed in the middle-aged and the older group. All of the main effects were found in accuracy, but not reaction times, suggesting that the percentage of accurate memory performance is a better indicator to reveal differences between categorical and coordinate spatial representations in the CATCOORD task. The age difference only existed in categorical change trials. Middle-aged participants were more accurate on judging categorical change trials than older participants. However, the age difference did not appear in coordinate change trials.

4.2.3.1.2 Dot-Cross task

Figure 4-13 shows both middle-aged and older participants' accuracy performance for the dot-cross task. A categorical advantage effect was not significant in the middle-aged group ($F(1,19)=4.34$, $p=0.051$). There was no hemispheric effect or interaction between the spatial relations and the hemispheres in the middle-aged group (Fs<1). For the older group, none of the main effects for the spatial relations and the hemispheres were found (Fs<1). However, the interaction between the spatial relations and the hemispheres was significant ($F(1,47)=4.37$, $p=0.042$). Although neither of the variables showed a significant effect on the interaction, the categorical change trials were performed better when the stimuli were presented on the left hemisphere and the coordinate spatial changed trials showed better performance when the stimuli were presented to the right hemisphere (Figure 4-13). When comparing accuracy of performance between the middle-aged and older group, effect of group was not found (F<1.). Overall, the categorical advantage effect, which has been consistently found in the young population, was not observed in the middle-aged or older groups. More importantly, the hemispheric specificity for processing categorical and coordinate spatial relations was observed in the older group, which indicates that the hemispheric lateralisation effects are not influenced by age.

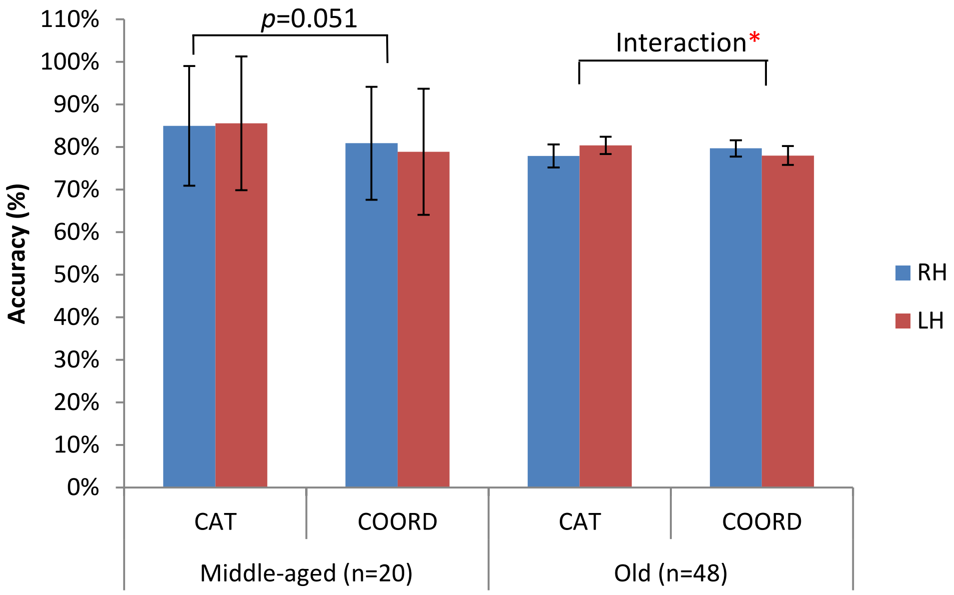


Figure 4-13. Accuracy for the middle-aged and the old group in the dot-cross task. '*' indicates $p<0.05$.

Figure 4-14 shows the result of reaction times of the dot-cross task for both middle-aged and older participants. The middle-aged group did not show any difference in responding to either categorical or coordinate spatial relations ($F(1,19)=2.34$, $p=0.143$) or when the stimuli were presented to different hemispheres ($F<1$). The interaction between the spatial relations and both hemispheres was not significant ($F<1$). Similarly, none of the main effects of the spatial representations and the interaction between the two variables were significant in the older group (Fs<1). In addition, while older participants seemed to take a slightly longer time to react to the trials than middle-aged participants, the difference between the two groups was not significant ($F(1,65)=1.53$, $p=0.220$).

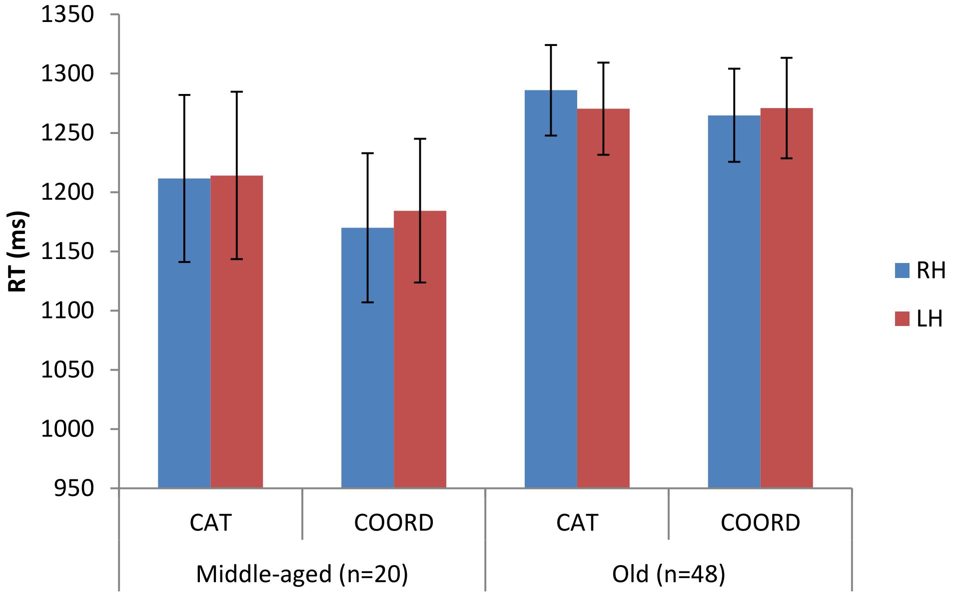


Figure 4-14. Reaction times for the middle-aged and the old group in the dot-cross task.

In sum, the hemispheric lateralisation effect did not present in the middle-aged group but did in the older group. Older adults performed more accurately in judging categorical trials when the stimuli were presented on the left hemisphere and they were also better in judging coordinate trials if the stimuli were presented on the right hemisphere. In addition, a pattern of the lateralisation effect in reaction time was shown in the older group. Overall, both accuracy and RT are useful indicators to examine the hemispheric specialisation effects for categorical and coordinate spatial process in the dot-cross task.

4.2.3.2 Neuropsychological battery

Means and standard deviations of each of the neuropsychological tests as well as the comparisons between the middle-aged and older group are presented in Table 4-4. The results suggest that the older group did not perform significantly differently from the middle-aged group in most of the tests apart from on a visuo-spatial test: VPT ($t(69)=2.62$, $p=0.010$). Older participants performed significantly worse than the middle-aged group in memorising the visual patterns. Other spatial ability tests (ORT:POM and COM) and attention-executive functions test (Stroop) did not reveal a significant difference between the middle-aged and old group.

The line-bisection task was included to extend the previous finding of hemispheric asymmetry of spatial attention in young participants to the older population. Hausmann (2005) utilised the task to show gender differences in segmenting a line; males were biased to the left while females were biased to the right when segmenting the line. If the hemispheric asymmetry occurs in the older population, the results could be further linked with the dot-cross task to explore the hemispheric specificity for spatial processes in ageing. However, the task did not demonstrate the hemispheric asymmetry for both genders in the current study. Both men and women showed a left side bias regardless of which hand they used to segment the line (Left hand: $t(69)=-1.02$, $p=0.313$; Right hand; $t(69)=-0.056$, $p=0.956$). Hence the hemispheric asymmetry effect was not replicated in the older population and the task was excluded in further analysis.

Table 4-5 depicts correlations between age and each neuropsychological task. Overall, age associated with most of the performance of the neuropsychological tasks except for an attention and executive function test (digit span (backward)), verbal ability tests (Rey-recall, recognition tests, and digit span (forward)) and a spatial ability test (ORT:COM task).

Table 4-4. Neuropsychological results for the middle-aged (n=20) and the older group (n=51).

	Middle-aged group		Older group				
	Mean	SD	Mean	SD	*t*	*p*	Cohen's *d*
Psychomotor tests							
Trail making test (part A) (sec.)	34.41	16.22	33.73	12.05	0.19	0.85	0.04
DSST (symbols/sec)	0.66	0.17	0.6	0.16	1.51	0.14	0.36
Attention and executive function tests							
Trail making (part B) (sec.)	64.11	25.8	74.82	47.5	-0.95	0.34	-0.28
Stroop (score)	-53.25	23.66	-69.02	34.09	1.89	***0.06***	0.54
Digit span (backward) (digit)	5	1.38	5.27	1.48	-0.72	0.48	-0.19
Verbal ability tests							
Rey: Learning (word)	54.2	8.41	50.02	10.99	1.53	0.13	0.43
Rey: Delayed recall (%)	86.81	13.11	83.29	17.55	0.81	0.42	0.23
Rey: Recognition (word)	13	2.15	13.06	2.18	-0.1	0.92	-0.03
Digit span (forward) (digit)	6.75	1.07	6.9	1.32	-0.46	0.65	-0.12
Spatial ability tests							
VPT (max. span)	8.75	1.21	7.65	1.72	2.62	0.01	0.74
SSP (max. span)	5.75	0.85	5.43	1.19	1.09	0.28	0.31
ORT: POM (mm)	175.75	42.62	195.56	40.95	-1.81	***0.07***	-0.47
ORT: OLB (% of errors)	22.25	20.29	30.98	23.39	-1.47	0.15	-0.40
ORT: COM (mm)	298	98.36	353.2	125.74	-1.76	***0.08***	-0.49
LBT: Right hand (Male; Female) (cm)	-1.59 ; -0.77	3.13; 2.8	-0.82 ; -1.03	2.33; 4.07	-0.34	0.74	-0.08
LBT: Left hand (Male; Female) (cm)	-1.6 ; -1.35	3.3; 3.1	1.27 ; -1.01	2.73; 2.89	-0.21	0.83	-0.54

Table 4-5. Spearman correlations between age and the neuropsychological tasks in all participants (i.e. middle-aged and older participants).

n=71	Age	Trail (A)	DSST	Trail (B)	Stroop	Digit span (backward)	Rey: Learning	Rey: Recall	Rey: Recogniti on	Digit span (forward)	VPT	SSP	ORT:POM	ORT:OLB	ORT:COM
Age	1														
Trail (A)	0.257*	1													
DSST	-0.436***	-0.531***	1												
Trail (B)	0.312**	0.545***	-0.691***	1											
Stroop	-0.466***	-0.351**	0.713***	-0.476***	1										
Digit span (backward)	-0.087	-0.234*	0.382**	-0.489***	0.280*	1									
Rey: Learning	-0.301*	-0.518***	0.498***	-0.525***	0.400**	0.243*	1								
Rey: Recall	-0.160	-0.352**	0.407***	-0.345**	0.374**	0.213	0.557***	1							
Rey: Recognition	-0.085	-0.374**	0.239*	-0.259*	0.216	0.065	0.499***	0.460***	1						
Digit span (forward)	-0.098	-0.356**	0.403***	-0.434**	0.386**	0.522***	0.279*	0.104	0.168	1					
VPT	-0.476**	-0.205	0.276*	-0.226	0.243*	0.047	0.097	-0.090	-0.082	0.087	1				
SSP	-0.366**	-0.219	0.334**	-0.328**	0.277*	0.379**	0.306**	0.258*	0.129	0.299*	0.249*	1			
ORT:POM	0.439***	0.219	-0.286*	0.226	-0.190	-0.091	-0.266*	-0.029	-0.253*	-0.008	-0.489***	-0.226	1		
ORT:OLB	0.351**	0.386**	-0.461***	0.408**	-0.295*	-0.383**	-0.468***	-0.459***	-0.357**	-0.227	-0.099	-0.219	0.328**	1	
ORT:COM	0.225	0.275*	-0.494***	0.371**	-0.364**	-0.249*	-0.437***	-0.432***	-0.316**	-0.199	-0.201	-0.218	0.354**	0.578***	1

N.B. "*" post hoc analysis is significant at the 0.05 level (2-tailed); "**" post hoc analysis is significant at the 0.01 level (2-tailed); "***" post hoc analysis is significant at the 0.001 level (2-tailed)..

4.2.3.3 Exploratory analyses

The aim of the exploratory analyses was to explore possible different cognitive profiles between the higher- and lower-performance groups in a series of cognitive neuropsychological tasks. In order to observe the difference between higher- and lower-function people when performing a cognitive task, older participants were first divided into higher-performance (OH) and lower-performance (OL) group according to all aspects of their cognitive performance, including psychomotor speed, attention and executive functions, verbal ability, and spatial ability. Although evidence from the primary analysis suggests that the middle-aged and older group did not differ in most of the neuropsychological tests, older participants with better performance and poorer performance may show different cognitive profiles when performing these tasks. A statistical correlation methodology was performed to observe any difference between the OH and OL group. After understanding the cognitive profile in OH and OL groups, a more objective analysis methodology, a principal components analysis (PCA), was applied to observe the contributions of different cognitive functions to better and poorer performance. The characteristic of PCA is that it extracts and generalises major cognitive functions from the raw data and avoids artificial classification, which may lead to biased conclusions. Finally, the Spearman correlation analysis and multiple linear regression methodology were carried out to observe recruitments of cognitive functions/components between the OH and OL group when performing visuo-spatial memory tasks, i.e. the CATCOORD task and the dot-cross task.

4.2.3.4 Define Old-higher (OH) and Old-lower (OL) groups

A standard Z score was derived from each test for each participant. The Z scores of all cognitive abilities: psychomotor ability, attention and executive function, verbal ability and spatial ability were averaged (i.e. mean of the Z scores). The mean Z score was set as a criterion to divide older participants into the OH and OL groups. Participants whose Z score was higher than the median were grouped into the OH group and those whose Z score was below the median were allocated to the OL group. Table 4-6 shows demographic information of the two groups; they did not differ in age, NART, or years of education. The difference between the OH and the OL group is not confounded by these demographic factors.

Table 4-6. Demographic information of OH and OL group.

	OH (n=25)	OL (n=26)		
	Mean (SD)	Mean (SD)	*t*	*p*
Age	67.60 (8.68)	69.38 (7.92)	-0.77	0.45
NART	120.00 (6.24)	118.65 (6.11)	0.78	0.44
Years of education	15.68 (2.94)	14.50 (3.08)	1.40	0.17

As expected, the OH and OL group showed significant differences in most of the neuropsychological tasks apart from the visual pattern test (VPT) (see Table 4-7). In addition to that, general information such as age, the predicted verbal IQ: NART, and years of education were included as covariate variables within the analysis to observe whether any of these factors contributes to good or poor cognitive performance in ageing. Figure 4-15 shows examples of the OH and OL performance on two cognitive tasks: Trail A and ORT:COM. The increased reaction time for Trail A means poorer performance. The results of ORT:COM showed the difference of distances between the allocated items by participants and the correct positions. The greater difference in distance also means poorer performance. Table 4-8 shows that most of the tasks still showed a significant group difference even after covarying for age, NART score, or years of education. While VPT performance remained an insignificant result between the OH and OL group, the group difference for Rey-AVLT: Recognition and ORT:POM also became non-significant after covariate adjustment for age. In addition, age affected the OH and OL group performance on spatial ability in particular. That is, the older the participants, the worse performance they showed on spatial ability. NART showed significant impacts on attention-executive ability for the OH and the OL group. The results of years of education, however, show significant covariate effects with all aspects of cognitive function. The significant effect of the covariate variables existed in some but not all tasks relating to each cognitive ability, so it is speculated to be task-dependent. In general, age impacts on spatial ability and NART affects attention-executive functions. Years of education, on the other hand, do not affect a specific cognitive ability in ageing.

Table 4-7. Means and standard deviations (SD) in the OH and OL group for each task separately and their comparison analysis.

	OH (n=26)		OL (n=25)			
	Mean	SD	Mean	SD	*t*	*p*
Psychomotor ability						
Trail making test (part A) (sec)	28.04	6.25	39.66	13.79	-3.9	*<0.001*
DSST(symbols/sec)	0.7	0.12	0.49	0.13	6.13	*<0.001*
Attention and executive function						
Trail making (part B) (sec)	55.24	17.46	95.19	59.44	-3.28	*0.002*
Stroop (score)	-55.18	26.49	-83.41	35.6	3.22	*0.002*
Digit span (backward) (digit)	6.08	1.2	4.44	1.29	4.69	*<0.001*
Verbal ability						
Rey: Learning (word)	55.96	5.65	43.84	11.84	4.69	*<0.001*
Rey: Delayed recall (%)	92.59	9.77	73.63	18.74	4.56	*<0.001*
Rey: Recognition (word)	13.81	1.33	12.28	2.61	2.65	*0.011*
Digit span (forward) (digit)	7.5	1.14	6.28	1.21	3.71	*0.001*
Spatial ability						
VPT (unit)	8	1.7	7.28	1.7	1.52	0.14
SSP (unit)	6.04	1.04	4.8	1	4.34	*<0.001*
ORT: POM (mm)	180.28	38.81	211.45	37.54	-2.91	*0.005*
ORT:OLB (% of errors)	17.69	14.65	44.8	22.94	-5.05	*<0.001*
ORT:COM (mm)	287.73	81.53	421.28	128.61	-4.45	*<0.001*

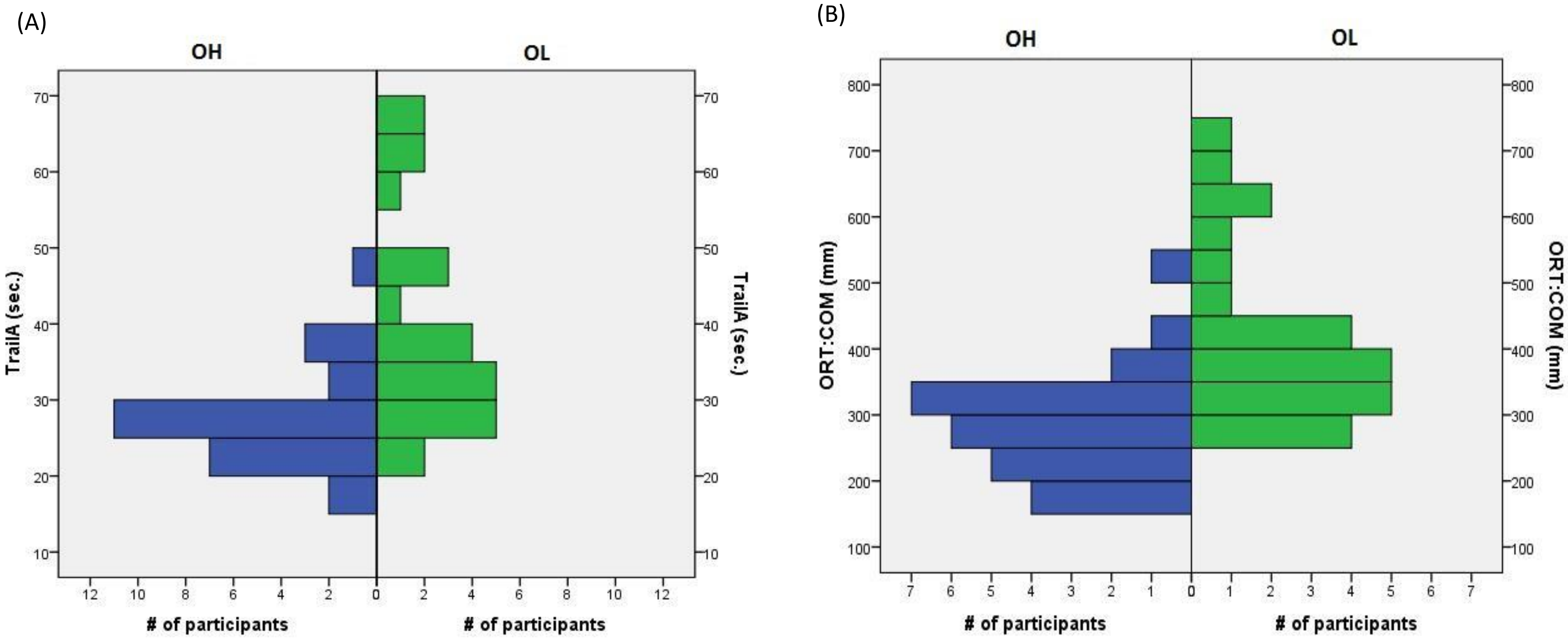


Figure 4-15. Histograms of OH and OL performance for (A) Trail A and (B) ORT:COM.

Table 4-8. Group effect of OH vs. OL group (including age, NART, and years of education as covariates).

Covariate variable		Age		NART		Years of education	
	df	*F*	*P*	*F*	*P*	*F*	*P*
Psychomotor ability							
Trail making test (part A)	(1, 48)	5.287	0.026^^	13.303	0.001	14.391	<0.001
DSST	(1, 48)	21.174	<0.001	39.509	<0.001^^	40.517	<0.001^^
Attention and executive function							
Trail making (part B)	(1, 48)	5.714	0.021	9.815	0.003^^	10.745	0.002^^
Stroop	(1, 48)	4.027	0.050	8.735	0.005^^	9.801	0.003^
Digit span (backward)	(1, 48)	13.127	0.001	19.909	<0.001^	21.009	<0.001
Verbal ability							
Rey: Learning	(1, 48)	11.668	0.001	19.865	<0.001^	21.690	<0.001^
Rey: Delayed recall	(1, 48)	13.367	0.001	20.116	<0.001	20.170	<0.001
Rey: Recognition	(1, 48)	2.198	0.145	6.308	0.015	6.720	0.013
Digit span (forward)	(1, 48)	9.049	0.004	2.631	0.001^^	13.049	.001
Spatial ability							
VPT	(1, 48)	0.009	0.926^^	1.454	0.234^	1.847	0.180^
SSP	(1, 48)	7.655	0.008^	16.754	<0.001	17.868	<0.001
ORT: POM	(1, 48)	1.463	0.232^^	7.617	0.008	8.034	0.007^
ORT:OLB	(1, 48)	12.301	0.001^	23.484	<0.001	24.570	<0.01
ORT:COM	(1, 48)	13.063	0.001	17.662	<0.001^	18.929	<0.001

N.B. "^" means the effect of covariate variable is significant at the 0.05 level (2-tailed); "^^" means the effect of covariate variable is significant at the 0.01 level (2-tailed).

The correlation for the OH and OL group was performed to investigate different approaches in performing the cognitive tasks. The non-parametric Spearman correlation was adopted in order to avoid bias driven by oldest-old participants i.e. people who are aged above 70. The result of the Spearman correlation for the OH group is presented in Table 4-9. There are a few correlations between different tasks yet there was no clear pattern of one measure being strongly correlated with another. On the other hand, the OL group linked various different cognitive abilities to each other while performing a cognitive task (see Table 4-10). The correlation patterns are different between the OH and OL group.

To conclude, the OH and OL group performed significantly different in most of the neuropsychological tests except VPT. While psychomotor speed and spatial ability were particularly affected by age, no specific cognitive function was targeted by age, NART or years of education. Different cognitive profiles were operating in the different groups as more correlations within the neuropsychological battery were found in the OL group and fewer correlations were found in the OH group. Since the current analysis has demonstrated the different cognitive strategies applied by the OH and OL group, the next step is to incorporate the middle-aged group into the comparison and to observe the neuropsychological profiles among the three groups.

Table 4-9. Spearman correlations between the standard neuropsychological tasks in the OH group.

OH (n=26)	Overall ability	Trail (A)	DSST	Trail (B)	Stroop	Digit span (backward)	Rey: Learning	Rey-: Delayed recall	Rey: recognition	Digit span (forward)	VPT	SSP	ORT: POM	ORT: OLB	ORT: COM
Overall ability	1														
Trail (A)	-0.391*	1													
DSST	0.485*	-0.167	1												
Trail (B)	-0.388	0.273	-0.499**	1											
Stroop	0.138	-0.05	0.605**	-0.231	1										
Digit span (backward)	0.352	0.141	0.224	-0.166	0.309	1									
Rey: Learning	0.440*	-0.301	0.155	-0.419*	0.138	-0.113	1								
Rey: Delayed recall	0.207	0.005	0.093	-0.194	0.132	-0.085	0.315	1							
Rey: Recognition	0.229	-0.127	-0.184	-0.282	-0.077	0.051	0.395*	0.338	1						
Digit span (forward)	0.217	-0.296	0.289	-0.166	0.457*	0.251	0.036	-0.151	0.169	1					
VPT	0.107	-0.228	0.076	-0.044	0.102	0.017	-0.112	-0.533**	-0.311	0.094	1				
SSP	0.245	0.148	0.248	-0.18	0.276	0.365	0.055	0.015	-0.168	0.105	0.238	1			
ORT: POM	-0.08	0.049	0.102	-0.035	0.269	0.284	0.117	0.414*	0.004	0.317	-0.394*	0.3	1		
ORT: OLB	-0.531**	0.004	-0.124	0.131	0.114	-0.03	-0.154	-0.443*	-0.182	0.204	0.209	0.156	0.272	1	
ORT: COM	-0.126	-0.274	0.061	-0.32	0.078	0.37	-0.067	-0.142	-0.032	-0.01	0.085	-0.07	0.121	0.248	1

N.B. ***** post hoc analysis is significant at the 0.05 level (2-tailed); ****** post hoc analysis is significant at the 0.01 level (2-tailed); ******* = post hoc analysis is significant at the 0.001 level (2-tailed).

Table 4-10. Spearman correlations between standard neuropsychological tasks in the OL group.

OL (n=25)	Overall ability	Trail (A)	DSST	Trail (B)	Stroop	Digit span (backward)	Rey: Learning	Rey: Delayed recall	Rey: recognitio n	Digit span (forward)	VPT	SSP	ORT: POM	ORT: OLB	ORT: COM
Overall ability	1														
Trail (A)	-0.693***	1													
DSST	0.612**	-0.677***	1												
Trail (B)	-0.66***	0.469*	-0.518**	1											
Stroop	0.552**	-0.44*	0.642**	-0.631**	1										
Digit span (backward)	0.281	0.154	0.44	-0.376	0.34	1									
Rey: Learning	0.732***	-0.478*	0.304	-0.253	0.237	0.028	1								
Rey: Delayed recall	0.509**	-0.515**	0.13	-0.28	0.267	-0.137	0.531**	1							
Rey: Recognition	0.566**	-0.471*	0.339	-0.163	0.303	-0.092	0.634**	0.572**	1						
Digit span (forward)	0.517**	-0.348	0.407*	-0.453*	0.658***	0.51**	0.329	0.049	0.024	1					
VPT	0.615**	-0.523**	0.428*	-0.72***	0.441*	0.065	0.333	0.148	0.218	0.433*	1				
SSP	0.647***	-0.565**	0.495*	-0.437*	0.391	0.228	0.362	0.232	0.188	0.447*	0.421*	1			
ORT: POM	-0.525**	0.263	-0.309	0.489*	-0.448*	-0.272	-0.228	-0.235	-0.311	-0.161	-0.514**	-0.437*	1		
ORT: OLB	-0.543**	0.423*	-0.32	0.237	-0.422*	-0.038	-0.502*	-0.319	-0.428*	-0.213	-0.167	-0.147	0.22	1	
ORT: COM	-0.506**	0.234	-0.306	0.405*	-0.365	-0.35	-0.497*	-0.212	-0.533**	-0.116	-0.249	-0.143	0.332	0.519**	1

N.B. ‘*’=post hoc analysis is significant at the 0.05 level (2-tailed); ‘**’= post hoc analysis is significant at the 0.01 level (2-tailed); ‘***’= post hoc analysis is significant at the 0.001 level (2-tailed).

4.2.3.5 Comparisons for the middle-aged, OH, and OL group

Different cognitive recruitment between the OL and OH group was shown in the previous section. The following analysis compares cognitive performance in the three groups, middle-aged vs. OH vs. OL group, in order to observe factors that may contribute to good or poor cognitive function in ageing. Table 4-11 shows the three groups comparison for the neuropsychological tasks. The OH group showed significantly better performance than the OL group in almost all of the tasks except VPT. Middle-aged participants performed better than the OL group in the majority of the cognitive tasks apart from the Trail making task (A), digit span memory test (both forward and backward), and Rey-AVLT: recognition task. Interestingly, the OH group showed even better performance than the middle-aged group on the two subtests of the digit span memory test. This result indicates that age may not be the only factor to determine good or poor performance in the current study.

The demographics factors, age, years of education and NART, were included as covariates among the three groups, for the purpose of understanding how these three factors affect participants' performance (see Table 4-12). The results showed that most cognitive performance including psychomotor ability and spatial ability was affected by age, which was consistent with the previous analysis. Performance on other tasks, such as Stroop and Rey-AVLT:recognition task, was also affected by age. NART influenced performance on tasks that are relevant to psychomotor ability, attention and executive function but not spatial ability. The predicted IQ did not affect spatial ability.

The results from the current analyses suggest that age shows a manifest effect for psychomotor and spatial ability performance. The influence of NART and years of education on cognitive performance was less clear. However, age may not play a fully defining role in affecting neuropsychological performance, as OH participants performed even better than middle-aged participants in some of the tasks. For the purpose of exploring different cognitive profiles that may differentiate higher- and lower-functioning adults, the following section will firstly mix both middle-aged and older participants and then divide the participants into a higher-performance (HP) and lower-performance (LP) group. In this case, possible confounds introduced by age could be eliminated in order to focus on investigating the differences between good and poor cognitive performance adults.

Table 4-11. Comparisons of the three groups (middle-aged vs. OH vs. OL) for each neuropsychological task.

	df	*F*	*p*	Post-hoc comparison
Psychomotor ability				
Trail making test (part A)	(2, 68)	5.57	0.006	OH>OL***
DSST	(2, 68)	16.55	<0.001	OH>OL*** MidAge>OL***
Attention and executive function				
Trail making (part B)	(2, 68)	7.12	0.002	OH>OL*** MidAge>OL**
Stroop	(2, 68)	7.97	0.001	OH>OL*** MidAge>OL***
Digit span (backward)	(2, 68)	10.7	<0.001	OH>OL*** OH>MidAge **
Verbal ability				
Rey: Learning	(2, 68)	13.11	<0.001	OH>OL*** MidAge>OL***
Rey: Delayed recall	(2, 68)	11.5	<0.001	OH>OL*** MidAge>OL**
Rey: Recognition	(2, 68)	3.43	0.038	OH>OL*
Digit span (forward)	(2, 68)	7.35	0.001	OH>OL*** OH>MidAge *
Spatial ability				
VPT	(2, 68)	4.85	0.011	MidAge>OL**
SSP	(2, 68)	11.04	<0.001	OH>OL*** MidAge>OL**
ORT: POM	(2, 68)	5.78	0.005	OH>OL** MidAge>OL***
ORT:OLB	(2, 68)	13.78	<0.001	OH>OL*** MidAge>OL***
ORT:COM	(2, 68)	12.34	<0.001	OH>OL*** MidAge>OL***

N.B. '*' = post hoc analysis is significant at the 0.05 level (2-tailed); '**' = post hoc analysis is significant at the 0.01 level (2-tailed); '***' = post hoc analysis is significant at the 0.001 level (2-tailed).

Table 4-12. The group effects of middle-aged, OH, and OL group after covariate with Age, NART, and years of education.

		Age			NART			Years of education		
	df	*F*	*P*	*Post-hoc (LSD)*	*F*	*P*	*Post-hoc (LSD)*	*F*	*P*	*Post-hoc (LSD)*
Psychomotor ability										
Trail making test (part A)	(2, 67)	7.297	0.001^^	OH>MidAge**	5.100	0.009	OH>OL**	5.440	0.006	OH>OL**
DSST	(2, 67)	9.862	<0.001^	OH>OL*** OH>MidAge*	19.408	<0.001^^	OH>OL*** MidAge>OL***	16.110	<0.001^	OH>OL*** MidAge>OL***
Attention and executive function										
Trail making (part B)	(2, 67)	4.439	0.015	OH>OL**	9.176	<0.001^^	OH>OL** MidAge>OL***	6.845	0.002^^	OH>OL** MidAge>OL*
Stroop	(2, 67)	2.864	0.064^	OH>OL*	9.035	<0.001	OH>OL** MidAge>OL***	7.495	0.001	OH>OL** MidAge>OL**
Digit span (backward)	(2, 67)	9.998	<0.001	OH>OL*** OH>MidAge*	9.775	<0.001^^	OH>OL*** MidAge>OL*	10.367	<0.001	OH>OL*** OH>MidAge**
Verbal ability										
Rey: Learning	(2, 67)	7.308	0.001	OH>OL**	13.821	<0.001	OH>OL*** MidAge>OL***	12.536	<0.001	OH>OL*** MidAge>OL***
Rey: Delayed recall	(2, 67)	8.674	<0.001	OH>OL***	11.265	<0.001	OH>OL*** MidAge>OL**	11.449	<0.001	OH>OL*** MidAge>OL**
Rey: Recognition	(2, 67)	3.986	0.023^	OH>MidAge*	3.352	0.041	OH>OL*	3.373	0.040	OH>OL*
Digit span (forward)	(2, 67)	6.714	0.002	OH>OL** OH>MidAge*	7.482	0.001^^	OH>OL*** MidAge>OL*	7.070	0.002	OH>OL*** OH>MidAge*
Spatial ability										
VPT	(2, 67)	0.113	0.894^^	-	5.446	0.006	MidAge>OL**	4.553	0.014^	MidAge>OL**
SSP	(2, 67)	7.005	0.002^	OH>OL** OH>MidAge*	11.070	<0.001	OH>OL*** MidAge>OL**	10.541	<0.001	OH>OL*** Midage>OL**
ORT: POM	(2, 67)	2.583	0.083^^	OH>MIdAge*	5.493	0.006	OH>OL** MidAge>OL*	5.361	0.007	OH>OL** MidAge>OL**
ORT:OLB	(2, 67)	7.958	0.001^	OH>OL**	14.031	<0.001	OH>OL*** MidAge>OL***	13.249	<0.001	OH>OL*** MidAge>OL***
ORT:COM	(2, 67)	7.231	0.001	OH>OL*** MidAge>OL*	12.917	<0.001	OH>OL*** MidAge>OL***	11.826	<0.001	OH>OL*** MidAge>OL***

N.B. '^'=covariate effect p<0.05. '^^'=covariate effect p<0.01. '*'=post hoc analysis p<0.05. '**'=post hoc analysis p<0.01. '***'=post hoc analysis p<0.001.

4.2.3.6 Age exclusion

The current study revealed that some older adults showed better cognitive performance than middle-aged adults, which indicates that the effect of the “physical age” could be overestimated. Alternatively, age-related cognitive decline may occur even earlier than the age of 60. Table 4-9 and Table 4-10 have demonstrated different cognitive profiles in the OH and OL group, specifically that the OL group revealed wide-spread correlations across different cognitive abilities while performing the tasks. However, as can be seen from Table 4-13, three times more of the oldest-old adults (age over 70) were categorised into the OL group than the OH group. Therefore, the significant correlations which emerged in the OL group may be driven by these oldest-old participants. In order to avoid possible unforeseen confounds, such as slow motor speed introduced by older age, the following exploratory analysis omitted participants who were aged above 70 years old. The middle-aged participants recruited in the current study showed a great variety of cognitive performance and some of their cognitive performance was even poorer than older adults. Therefore, middle-aged and older adults were joined together and split into the higher- and lower-performance group to observe possible different cognitive profiles recruited by the two groups. Table 4-14 shows that 8 out of 20 middle-aged participants were categorised in the lower-performance group and 12 of the middle-aged participants were assigned into the higher-performance group. By excluding the oldest-old participants and reorganising the middle-aged and older groups, 55 participants (age range between 40 and 69) were finally divided into the higher-performance (HP) and lower-performance (LP) groups in accordance with their overall cognitive performance. Table 4-15 presents demographic information for the HP and LP groups that are involved in the following analyses. Importantly, there was no significant difference in age, NART, or years of education between the HP and LP group. Any different cognitive profile observed from the HP and LP group could not be attributed to these factors but their cognitive ability.

Table 4-13. Mean age for middle-aged, old-higher, and old-lower group.

Group	Middle-aged	OH		OL	
Age range	45-59	60-69	70-94	60-69	70-94
# of participants	20	22	4	13	12
Mean age (SD)	52.15 (4.37)	63.09 (2.41)	73.5 (3.79)	65.46 (2.73)	80.08 (7.91)

Table 4-14. Distributions of higher- and lower-performance group across different age ranges.

Group	Higher-performance group			Lower-performance group		
Age range	45-59	60-69	70-94	45-59	60-69	70-94
# of participants	12	20	4	8	15	12
Mean age (SD)	52.08 (4.52)	63.25 (2.43)	73.5 (3.79)	52.25 (4.43)	64.93 (2.94)	80.08 (7.91)

Table 4-15. Demographic information of the new higher- and lower-performance group.

	(New) **Higher-performance group (HP) (n=28)**	(New) **Lower-performance group (LP) (n=27)**		
	Mean (SD)	Mean (SD)	*t*	*p*
Age	59.00 (5.97)	60.37 (7.37)	-0.75	0.45
NART	118.18 (6.74)	117.67 (7.95)	0.26	0.80
Years of education	15.77 (2.67)	15.63 (2.84)	0.19	0.85

4.2.3.7 Correlations for Higher-performance (HP) and Lower-performance (LP) with the neuropsychological tasks

Table 4-16 and Table 4-17 present the correlations of neuropsychological tests for the HP and LP groups. The HP and LP showed similar cognitive profile to the previous comparisons for the OH and OL groups. Higher-performance participants showed less correlation across different neuropsychological tests than the LP group. In the HP group, the overall ability, i.e. the sum of performance on psychomotor tests, attention and executive function tests, verbal tests, and spatial tests, showed correlations with all cognitive abilities, including positive correlations with psychomotor ability (DSST), attention and executive function ability (digit span backward memory task), verbal ability (digit span forward memory task) and spatial ability (VPT) and a negative correlation with Trail making (B). These results suggest that the overall ability is correlated with all dimensions of cognitive ability. The correlations between psychomotor ability (DSST) and attention and executive function ability (Trail making (B), Stroop, Digit span (backward)) indicate that the two cognitive domains are associated with each other. The performance on psychomotor speed would affect attention and executive functions and vice versa. Several other correlations between attention and executive functions, verbal ability, and spatial ability were found in the neuropsychological battery but the correlations only existed in one or two of the tasks of the classified cognitive ability.

Similar to the findings with the OL group, the LP group showed more correlations than the HP group across different cognitive tasks. Different cognitive abilities were strongly associated with each other in the LP group. The overall ability was correlated with cognitive ability in all aspects, including psychomotor speed (Trail making (A), DSST), attention and executive functions (Trail making (B), Stroop), verbal ability (Rey-AVLT: Learning and recognition test, and the digit span (forward) memory task) and spatial ability (ORT: POM and COM). In addition, psychomotor ability not only showed correlations with attention and executive function tasks but also verbal ability. Participants associated both executive functions and verbal ability when performing psychomotor related tasks. Similarly, verbal ability was applied when performing attention and executive function tasks. The attention and executive function ability was also found to be associated with the most difficult spatial task, ORT:COM. Overall, the LP group revealed more correlations across different cognitive abilities than the HP group.

Table 4-16. Pearson correlations between the neuropsychological tasks in the HP group.

HP group (n=28)	Overall ability	Trail (A)	DSST	Trail (B)	Stroop	*Digit span (backward)*	*Rey: Learning*	*Rey: Delayed recall*	*Rey: recognition*	*Digit span (forward)*	*VPT*	*SSP*	*ORT: POM*	*ORT: OLB*	*ORT: COM*
Overall ability	1														
Trail (A)	-0.364	1													
DSST	0.558**	-0.241	1												
Trail (B)	-0.503**	0.211	-0.476*	1											
Stroop	0.222	-0.109	0.416*	-0.050	1										
Digit span (backward)	0.436*	-0.219	0.498**	-0.371	0.122	1									
Rey: Learning	0.324	-0.144	0.147	-0.262	0.309	-0.159	1								
Rey: Delayed recall	0.034	-0.059	0.247	0.046	0.463*	-0.149	0.370	1							
Rey: Recognition	0.343	-0.073	0.134	-0.043	0.275	-0.133	0.189	0.411*	1						
Digit span (forward)	0.556**	-0.331	0.307	-0.231	0.187	0.637**	-0.118	-0.162	0.189	1					
VPT	0.395*	0.006	0.103	0.034	0.104	0.048	-0.010	-0.359	-0.358	0.022	1				
SSP	0.213	0.199	-0.211	-0.008	-0.153	0.126	0.030	-0.044	-0.204	0.038	0.263	1			
ORT: POM	-0.256	-0.209	0.138	-0.173	0.183	0.327	0.066	0.391*	-0.167	0.100	-0.448*	0.042	1		
ORT: OLB	-0.085	0.108	0.122	-0.053	-0.060	0.005	0.040	0.083	-0.322	-0.006	0.178	0.238	0.176	1	
ORT: COM	-0.137	-0.147	0.011	-0.198	-0.077	0.367	0.057	0.037	-0.191	0.035	-0.254	0.259	0.450*	-0.034	1

Table 4-17. Pearson correlations between the neuropsychological tasks in the LP group.

LP group (n=27)	Overall ability	Trail (A)	DSST	Trail (B)	Stroop	Digit span (backward)	Rey: Learning	Rey: Delayed recall	Rey: recognition	Digit span (forward)	VPT	SSP	ORT: POM	ORT: OLB	ORT: COM
Overall ability	1														
Trail (A)	-0.583**	1													
DSST	0.578**	-0.479*	1												
Trail (B)	-0.713***	0.454*	-0.762***	1											
Stroop	0.529**	-0.413*	0.778***	-0.771***	1										
Digit span (backward)	0.355	-0.012	-0.049	-0.293	0.078	1									
Rey: Learning	0.758***	-0.423*	0.450*	-0.463*	0.472*	0.167	1								
Rey: Delayed recall	0.349	0.108	0.179	-0.108	0.180	0.015	0.430*	1							
Rey: Recognition	0.553**	-0.586**	0.031	-0.022	-0.005	0.123	0.485*	0.089	1						
Digit span (forward)	0.566**	-0.302	0.309	-0.467*	0.485*	0.378	0.394*	0.081	0.228	1					
VPT	0.255	-0.141	0.321	-0.394*	0.215	-0.302	-0.015	0.011	-0.099	-0.062	1				
SSP	0.340	-0.068	0.024	-0.287	0.252	0.347	0.231	0.040	0.134	0.365	-0.051	1			
ORT: POM	-0.411*	0.346	-0.301	0.363	-0.287	0.169	-0.181	0.127	-0.214	0.093	-0.436*	-0.015	1		
ORT: OLB	-0.373	-0.009	-0.065	-0.033	0.063	-0.009	-0.347	-0.316	-0.225	-0.129	0.036	0.250	0.060	1	
ORT: COM	-0.506**	-0.047	-0.461*	0.481*	-0.409*	-0.190	-0.297	-0.267	0.090	-0.314	-0.202	-0.052	0.126	0.316	1

4.2.3.8 Components generated by principal component analysis (PCA)

In the previous analysis, the neuropsychological tests were grouped into neurocognitive domains according to their commonly described cognitive characteristics/processes. However, it is suggested that each of the cognitive tasks typically involves more than one cognitive process. For instance, one of the categorized spatial ability tests, ORM: OLB, involves not only spatial ability but also verbal, attention and executive abilities in order to memorize the location of the objects and plan to allocate them (Gallagher, Gray, & Kessels, 2014). Hence it is difficult to attribute cognitive tasks to specific cognitive domains. The result generated from subjective classification may mislead the results. Principal component analysis (PCA) provides an alternative solution by enabling the statistical classification to generalize components in accordance with the proportion of variance explained by the raw data (Bartholomew, Steele, Moustaki, & Galbraith, 2008). This computational methodology groups cognitive tasks that share common variance together, hence the results are more objective and are able to avoid artificial bias.

All the 14 neuropsychological tests were included in the PCA. After several omitted measures, six tests were excluded due to smaller loadings to a component. The analysis finally generalised 8 cognitive tasks into 3 components (Table 4-18). Component 1 included Stroop, DSST, and Trail making task (B), which were all relevant to attention and executive functions. It was named as ‘Attention-executive component’. ORM:OLB, Rey-AVLT: Recognition and Retention tests, which were highly related to verbal ability, were categorized in Component 2, ‘Verbal component’. Gallagher et al. (2014) examined the ORM task in great detail and found out that OLB was specifically correlated with verbal ability in bipolar patients but not in controls. They speculated that the correlation was caused by a verbal strategy of memorising the names of to-be-remembered objects in order to replace them in the same positions in the test phase. Finally, SSP and digit span backward memory test were included in the third component. Both tasks required short-term memory capacity hence this was called ‘STM component’. The following section will probe the relationships between these cognitive components and the tasks of interest. Both correlation and hierarchical multiple regression methods were adopted to observe cognitive strategy for the HP and LP groups when performing a visuo-spatial memory task.

Table 4-18. The final three components generalised via PCA.

Pattern Matrix[a]

	Component		
	1	2	3
Stroop_score	.893		
DDSToriginalSymbolPerSec	.842		
TrailB	-.811		
OLB		-.799	
AVLT_Recognition_CorrectA		.749	
RAVLT_retention		.678	
SSP			.847
Digitspan_Backward			.764

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.
a. Rotation converged in 4 iterations.

4.2.3.9 The relationship between the cognitive components and the tasks of interest

4.2.3.9.1 CATCOORD task

As mentioned previously, accuracy is a better indicator of performance for categorical and coordinate spatial representations in the CATCOORD task than reaction time (see section 4.2.3.1.1). Therefore, the following correlation analysis will focus on observing the relationship between the cognitive components and the accuracy of performance in the CATCOORD task. Table 4-19 shows the Pearson correlation for the CATCOORD task and the principal components. None of the components showed significant correlation with the task. There is no evidence that participants utilised a specific cognitive function to perform the task. Cognitive resources such as attention-executive functions, verbal ability, and short-term memory were equally recruited when performing the CATCOORD task. However, weighting of components may be different between higher- or lower-performance participants when undertaking the task. Table 4-20 shows the correlation between the cognitive components and the CATCOORD task in the HP and LP groups. The results showed that none of the cognitive components showed significant correlation with the task performance in either group. That is, neither the LP group nor the HP group showed additional recruitment of attention, executive functions, or verbal resources to perform the CATCOORD task.

Table 4-19. Pearson correlation for the CATCOORD task and the neuropsychological components.

	CATCOORD task (Acc.) (n=55)	
Cognitive component	CAT	COORD
Attention-executive	-0.049	0.186
Verbal	0.053	0.238
STM	0.184	0.071

Table 4-20. Pearson correlation for the higher- and lower-performance group in the CATCOORD task.

	HP group (n=28)		LP group (n=27)	
Cognitive component	CAT	COORD	CAT	COORD
Attention-executive	-0.237	0.326	0.084	-0.12
Verbal	-0.169	-0.045	0.14	0.299
STM	0.173	-0.143	0.18	0.077

4.2.3.9.2 Dot-Cross task

While accuracy was the most appropriate measure for the CATCOORD task, reaction time was a better index to reveal hemispheric lateralisation effect for categorical and coordinate spatial relations in the dot-cross task. Therefore, the following analysis will only involve RT performance from the dot-cross task. Note that one of the participants from the HP group did not complete the task; hence only 54 participants were involved in the analysis of the dot-cross task. The results for the three cognitive components and the task performance are presented in Table 4-21. None of the cognitive components showed significant correlation with the dot-cross task. Although the attention-executive and the short-term memory component showed trends of negative correlation with the dot-cross task while the verbal component showed positive correlation with the task, none of those reached a significant level. When carrying out the analysis with the HP and LP groups, the results showed different cognitive profiles between the HP and LP group (see Table 4-22). Only lower-function participants showed a significant positive correlation with the verbal component. However, the LP group did not show significantly slower response time than the HP group (1148ms vs. 1152ms, $F(1,52)=2.43$, $p=0.125$).

Table 4-21. Pearson correlation for the 3 principal components and the dot-cross task's performance.

	Dot-cross task (RTs) (n=54)			
Cognitive component	CAT_RH	CAT_LH	COORD_RH	COORD_LH
Attention-executive	-0.105	-0.193	-0.050	-0.058
Verbal	0.103	0.058	0.097	0.064
STM	-0.055	-0.061	-0.104	-0.080

Table 4-22. Pearson correlation for the 3 neuropsychological components and RT of the dot-cross task in the higher- and lower-performance groups.

	HP group (n=27)				LP group (n=27)			
Cognitive component	CAT_RH	CAT_LH	COORD_RH	COORD_LH	CAT_RH	CAT_LH	COORD_RH	COORD_LH
Attention-executive	-0.128	-0.220	-0.070	-0.028	0.055	-0.005	0.183	0.120
Verbal	-0.016	0.015	0.051	0.029	0.439*	0.390*	0.464*	0.404*
STM	-0.313 (p=0.112)	-0.274 (p=0.166)	-0.320 (p=0.104)	-0.329 (p=0.094)	0.257	0.260	0.205	0.244

'*' indicates $p<0.05$.

4.2.3.10 *Hierarchical multiple regression*

Hierarchical multiple regression utilises systematic analysis to illustrate the proportion of variance that is explained by each predictor (Field, 2009). In order to understand different issues, two types of analysis were carried out. The first method investigates whether cognitive ability (i.e. higher- or lower-performance group) can predict participants' performance on the CATCOORD and the dot-cross task. The second regression method addresses cognitive strategies employed by higher and lower performance groups. The underlying cognitive profiles for higher and lower cognitive function groups in older adults were explored.

1) Can the “group” be a predictor to estimate participants’ performance on a visuo-spatial memory task? Data from the 55 participants, regardless of their cognitive ability, were included in the regression model. The background variables, age and NART score (age was the first entry) were entered at the first step of the hierarchical regression, followed by the verbal component, the attention-executive component, and the STM component. The order of the cognitive components was entered strategically in order to investigate the impact of each cognitive component. The verbal component was thought to be an important variable to demonstrate possible ‘verbal scaffolding’ for a visuo-spatial STM task hence it was placed at the second step of the hierarchical model, after the variance from the background variables was accounted for. Moreover, the verbal component was placed last in a different hierarchical multiple regression model in order to observe whether the impacts of the verbal component existed after the variance from the other two cognitive components was explained. The order of the attention-executive and STM components were examined to observe their impacts on task performance. Finally, cognitive ability (i.e. “group”) was entered last in this analysis to investigate its impact on task performance after the variance of the background variables and the cognitive components were explained. The entry order of the group variable was manipulated if the results were significant. The background variables age and NART were always placed in the first step of the strategic regression model in order to explore their influence on the cognitive components and cognitive ability after the variance of the background variables were explained. The analysis is designed to examine whether the task performance could be predicted by any of these variables. Specifically, whether cognitive ability, i.e. the higher and lower performance groups, can predict performance on a visuo-spatial memory task.

2) In order to observe different patterns in the HP and LP groups, the background variables and the three cognitive variables were entered into a regression model separately. The hierarchical regression strategy was similar to the previous analysis except the last step (i.e. the ‘group’ variable) had been removed. This analysis would reveal the amount of variance

explained by each variable (i.e. the background variables and the cognitive variables) in the HP and LP groups.

Similar to the previous exploratory analysis (section 4.2.3.9), accuracy of performance was applied to the analysis with the CATCOORD task while RT performance was utilised with the analysis of the dot-cross task.

4.2.3.10.1 CATCOORD task

1) Using the 'group' as a model variable

The result of the strategic regression analysis showed that 13.5% of variance was explained by the background variables (i.e. age and NART) when performing coordinate change trials (see Model 1 in Table 4-23). Neither the cognitive composites nor higher/lower group could predict participants' performance for the CATCOORD task. Model 2 and Model 3 explored the entry order of the background variables. As can be seen in Model 2, when age was the first entry variable and NART was the second, age explained only 3.3% of variance for the coordinate performance (p=0.182). When NART was entered first (see Model 3), followed by age, NART only explained 2.8% of variance for the coordinate performance (p=0.224). Neither age nor NART accounted for a significant amount of variance change. It was only when the two variables were joined together that the amount of variance change made a significant contribution to the model. Order of variable entry was explored in other regression models. Since the current analysis focused on whether cognitive ability could predict performance on the CATCOORD task, the 'group' variable was entered at the second step in a regression model, after the background variables was entered. The 'group' variable did not show a significant proportion of variance even when only the variance from background variables was explained. When placing the verbal component last in a regression model (i.e. after the variance from the background variables, the attention-executive component, the STM component, and the group variable), it did not significantly change the amount of variance explained in the model. The findings suggest that neither 'group' nor 'verbal' variable could predict the task performance. In addition, the entry order of the attention-executive and STM component did not affect the findings.

Table 4-23. Hierarchical regression for the CATCOORD task ('Group' as a model variable).

	CAT				COORD			
	R^2	R^2 change	F for R^2 Change	*P*	R^2	R^2 change	F for R^2 Change	*p*
Model 1								
Age + NART	0.016	0.016	0.415	0.663	0.135	0.135	4.054	*0.023*
Verbal	0.017	0.002	0.088	0.768	0.163	0.029	1.739	0.193
Attention-executive	0.021	0.004	0.203	0.654	0.165	0.001	0.077	0.782
STM	0.081	0.060	3.196	0.080	0.165	0.000	0.008	0.928
Group	0.083	0.001	0.068	0.795	0.165	0.000	0.020	0.889
Model 2								
Age	0.016	0.016	0.840	0.364	0.033	0.033	1.833	0.182
NART	0.016	0.000	0.005	0.943	0.135	0.101	6.098	*0.017*
Verbal	0.017	0.002	0.088	0.768	0.163	0.029	1.739	0.193
Attention-executive	0.021	0.004	0.203	0.654	0.165	0.001	0.077	0.782
STM	0.081	0.060	3.196	0.080	0.165	0.000	0.008	0.928
Group	0.083	0.001	0.068	0.795	0.165	0.000	0.020	0.889
Model 3								
NART	0.006	0.006	0.313	0.578	0.028	0.028	1.513	0.224
Age	0.016	0.010	0.519	0.474	0.135	0.107	6.439	*0.014*
Verbal	0.017	0.002	0.088	0.768	0.163	0.029	1.739	0.193
Attention-executive	0.021	0.004	0.203	0.654	0.165	0.001	0.077	0.782
STM	0.081	0.060	3.196	0.080	0.165	0.000	0.008	0.928
Group	0.083	0.001	0.068	0.795	0.165	0.000	0.020	0.889

2) Higher-performance group vs. lower-performance group

Table 4-24 illustrates the hierarchical multiple regression model for the higher-performance and the lower-performance group when judging categorical and coordinate spatial changes. The results suggest that none of the predictors can estimate the categorical performance in either HP or LP group. On the other hand, age and NART explained 35.7% of variance in the higher-performance group but not the lower-performance group when judging coordinate spatial changes; this suggests that participants' demographic information could predict their performance on coordinate spatial judgments. Model 5 and Model 6 explored the entry order of background variables (see Table 4-25). The order of the background variables' entry could not predict categorical performance for the higher- and lower-performance group. However, the order entry of age and NART affected the task performance on coordinate spatial judgments for the HP group. Specifically, NART explained 33.1% of variance in the higher-performance group after the variance of age was accounted for (Model 5). There was no significant proportion of variance explained by age. Model 6 displays the reversed order for the background variables. The results showed that after the significant proportion of variance (17.8%) had been explained by NART, age accounted for significant additional variance (17.9%) when processing coordinate spatial relations (Model 6). Therefore, NART was a more influential predictor for the coordinate performance for the HP group. Moreover, order of the cognitive components was explored in different regression models. When the verbal component was allocated last into a regression model, it did not significantly change the amount of variance explained in the model. The entry order of the attention-executive and STM component did not affect the findings. While age and NART are important in estimating the task performance for the higher-performance group, none of the cognitive components could predict the performance for the CATCOORD task for the HP or LP group.

Table 4-24. Hierarchical regression for the CATCOORD task (higher- vs. lower-performance group).

Model 4	HP group				LP group			
CAT	R^2	R^2 change	F for R^2 Change	*P*	R^2	R^2 change	F for R^2 Change	*p*
Age + NART	0.012	0.012	0.147	0.846	0.019	0.019	0.236	0.791
Verbal	0.039	0.028	0.691	0.414	0.037	0.018	0.418	0.524
Attention-executive	0.126	0.087	2.293	0.144	0.045	0.008	0.183	0.673
STM	0.171	0.045	1.183	0.289	0.101	0.056	1.303	0.267
COORD								
Age + NART	0.357	0.357	6.925	*0.004*	0.036	0.036	0.453	0.641
Verbal	0.363	0.006	0.240	0.628	0.108	0.072	1.853	0.187
Attention-executive	0.373	0.011	0.386	0.541	0.137	0.029	0.734	0.401
STM	0.410	0.036	1.355	0.257	0.155	0.018	0.453	0.508

Table 4-25. Hierarchical regression for the CATCOORD task, exploring entry order of background variables (higher- vs. lower-performance group).

Model 5	HP group				LP group			
CAT	R^2	R^2 change	F for R^2 Change	*P*	R^2	R^2 change	F for R^2 Change	*P*
Age	0.011	0.011	0.288	0.596	0.017	0.017	0.433	0.517
NART	0.012	0.001	0.018	0.895	0.019	0.002	0.056	0.815
Verbal	0.039	0.028	0.691	0.414	0.037	0.018	0.418	0.524
Attention-executive	0.126	0.087	2.293	0.144	0.045	0.008	0.183	0.673
STM	0.171	0.045	1.183	0.289	0.101	0.056	1.303	0.267
COORD								
Age	0.026	0.026	0.692	0.413	0.030	0.030	0.771	0.388
NART	0.357	0.331	12.843	*0.001*	0.036	0.006	0.161	0.691
Verbal	0.363	0.006	0.240	0.628	0.108	0.072	1.853	0.187
Attention-executive	0.373	0.011	0.386	0.541	0.137	0.029	0.734	0.401
STM	0.410	0.036	1.355	0.257	0.155	0.018	0.453	0.508
Model 6	HP group				LP group			
CAT	R^2	R^2 change	F for R^2 Change	*P*	R^2	R^2 change	F for R^2 Change	*P*
NART	0.001	0.001	0.021	0.886	0.014	0.014	0.343	0.563
Age	0.012	0.011	0.275	0.605	0.019	0.006	0.141	0.711
Verbal	0.039	0.028	0.691	0.414	0.037	0.018	0.418	0.524
Attention-executive	0.126	0.087	2.293	0.144	0.045	0.008	0.183	0.673
STM	0.171	0.045	1.183	0.289	0.101	0.056	1.303	0.267
COORD								
NART	0.178	0.178	5.616	*0.026*	0.002	0.002	0.038	0.847
Age	0.357	0.179	6.950	*0.014*	0.036	0.035	0.868	0.361
Verbal	0.363	0.006	0.240	0.628	0.108	0.072	1.853	0.187
Attention-executive	0.373	0.011	0.386	0.541	0.137	0.029	0.734	0.401
STM	0.410	0.036	1.355	0.257	0.155	0.018	0.453	0.508

4.2.3.10.2 Dot-Cross task

1) Using the ‘group’ as a model variable

Cognitive ability, i.e. the ‘group’ variable, was found to be a sufficient predictor to identify the HP and LP group when making coordinate judgments in the dot-cross task (see Table 4-26, Model 1). Specifically, the cognitive ability predicted the significant proportion of the variance for the performance on the COORD_LH judgment (9.8%) and the COORD_RH judgment (9.3%). However, the significance disappeared when the group variable was allocated at the second entry of the regression model (Model 7), after the variance of background variables was accounted for. The entry order was crucial to reveal impacts of cognitive ability. Cognitive ability could estimate the performance of coordinate spatial judgments after the variance of the cognitive and background variables was explained. The verbal component consistently showed a trend of significance for predicting task performance in Model 7. However, the only significant finding occurred when coordinate spatial changes were presented on the right hemisphere. When the verbal component was placed last in a hierarchical regression model, it did not explain a significant proportion of variance for categorical and coordinate processing. Order of the attention and STM component was examined and no significant finding was found. Neither the attention-executive component nor the STM component could predict the performance for the dot-cross task.

Table 4-26. Hierarchical regression for the dot-cross task.

	CAT_LH				CAT_RH				COORD_LH				COORD_RH			
Model 1	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*
Age + NART	0.024	0.024	0.626	0.539	0.013	0.013	0.336	0.716	0.006	0.006	0.163	0.85	0.020	0.020	0.517	0.600
Verbal	0.031	0.008	0.389	0.535	0.028	0.015	0.781	0.381	0.011	0.005	0.238	0.628	0.029	0.009	0.487	0.489
Attention-executive	0.072	0.041	2.140	0.150	0.045	0.016	0.837	0.365	0.019	0.008	0.416	0.522	0.041	0.012	0.620	0.435
STM	0.075	0.003	0.159	0.692	0.051	0.006	0.311	0.580	0.030	0.011	0.545	0.464	0.065	0.024	1.207	0.277
Group	0.132	0.057	3.104	0.085	0.104	0.054	2.821	0.100	0.129	0.098	5.299	*0.026*	0.158	0.093	5.213	*0.027*
Model 7																
Age + NART	0.024	0.024	0.626	0.539	0.013	0.013	0.336	0.716	0.006	0.006	0.163	0.850	0.020	0.020	0.517	0.600
Group	0.058	0.034	1.801	0.186	0.033	0.020	1.047	0.311	0.059	0.052	2.773	0.102	0.070	0.050	2.706	0.106
Verbal	0.121	0.063	3.510	*0.067*	0.103	0.070	3.836	*0.056*	0.127	0.069	3.851	*0.055*	0.157	0.087	5.052	*0.029*
Attention-executive	0.131	0.010	0.559	0.458	0.104	0.001	0.053	0.819	0.128	0.001	0.061	0.805	0.157	0.000	0.022	0.883
STM	0.132	0.001	0.076	0.784	0.104	0.000	0.009	0.924	0.129	0.000	0.020	0.889	0.158	0.001	0.046	0.830

2) Higher-performance vs. lower-performance group

Table 4-27 illustrates that none of the background variables or the cognitive components explained the variance of the performance for the dot-cross task significantly in the HP group. However, the verbal component explained a significant amount of variance for task performance in the LP group. When performing categorical change trials, the verbal component explained 17.4% and 19.6% of variance when stimuli were presented on the left and right hemisphere, respectively. The verbal component also accounted for 15.5% and 19.4% of variance when coordinate changes were presented on the left and the right hemisphere, respectively. The result suggests that verbal ability could predict the task performance in the LP group. When the entry order of the attention-executive and STM component was reversed (Model 8), the STM component explained 15.7% of variance for the performance on the CAT_LH judgments (see Table 4-28). The attention-executive variable could not estimate performance for the dot-cross task.

Model 9 (Table 4-29) presents a regression model in which the verbal component was entered last. The results showed that verbal ability could still predict performance for the LP group, even after the variance from the background variables, the attention-executive and STM component was explained. The verbal component explained the significant proportion of the variance change when categorical changes were presented on the left hemisphere (16.4%) and the right hemisphere (17.9%) and when coordinate changes were presented on the right hemisphere (18.0%). However, no significance was found in the verbal component when coordinate changes were presented on the left hemisphere (14.1%, p=0.065). Order of the attention-executive and STM component in a regression model did not affect the findings. Neither attention-executive functions nor STM ability could predict the task performance for the HP and the LP groups.

The results indicate that verbal ability is a sufficient predictor to estimate the performance for the dot-cross task in the LP group.

Table 4-27. Higher- and lower-performance group hierarchical regression for the dot-cross task.

	HP group															
	CAT_LH				CAT_RH				COORD_LH				COORD_RH			
Model 4	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*
Age + NART	0.027	0.027	0.339	0.716	0.055	0.055	0.693	0.510	0.009	0.009	0.109	0.897	0.036	0.036	0.444	0.646
Verbal	0.028	0.001	0.017	0.898	0.055	0.001	0.015	0.904	0.010	0.001	0.019	0.891	0.037	0.001	0.036	0.852
Attention-Executive	0.057	0.029	0.681	0.418	0.072	0.017	0.409	0.529	0.010	0.000	0.002	0.967	0.045	0.007	0.168	0.685
STM	0.125	0.067	1.613	0.218	0.215	0.142	3.805	0.065	0.144	0.134	3.295	0.084	0.181	0.137	3.505	0.075
	LP group															
Age + NART	0.033	0.033	0.415	0.665	0.001	0.001	0.016	0.984	0.022	0.022	0.268	0.767	0.051	0.051	0.640	0.536
Verbal	0.208	0.174	5.061	*0.034*	0.197	0.196	5.611	*0.027*	0.177	0.155	4.330	*0.049*	0.244	0.194	5.897	*0.023*
Attention-Executive	0.208	0.001	0.017	0.896	0.198	0.001	0.021	0.886	0.181	0.005	0.126	0.726	0.256	0.012	0.346	0.563
STM	0.241	0.032	0.897	0.354	0.256	0.058	1.636	0.215	0.219	0.037	1.006	0.327	0.274	0.018	0.525	0.477

Table 4-28. Higher- and lower-performance group hierarchical regression for the dot-cross task (reversed entry of the attention-executive and the STM component).

	HP group															
	CAT_LH				CAT_RH				COORD_LH				COORD_RH			
Model 8	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*
Age + NART	0.027	0.027	0.339	0.716	0.055	0.055	0.693	0.510	0.009	0.009	0.109	0.897	0.036	0.036	0.444	0.646
Verbal	0.028	0.001	0.017	0.898	0.055	0.001	0.015	0.904	0.010	0.001	0.019	0.891	0.037	0.001	0.036	0.852
STM	0.111	0.083	2.050	0.166	0.212	0.157	4.369	*0.048*	0.140	0.130	3.336	0.081	0.181	0.144	3.865	0.062
Attention-Executive	0.125	0.014	0.325	0.574	0.215	0.003	0.080	0.781	0.144	0.004	0.098	0.757	0.181	0.000	0.003	0.955
	LP group															
Age + NART	0.033	0.033	0.415	0.665	0.001	0.001	0.016	0.984	0.022	0.022	0.268	0.767	0.051	0.051	0.640	0.536
Verbal	0.208	0.174	5.061	*0.034*	0.197	0.196	5.611	*0.027*	0.177	0.155	4.330	*0.049*	0.244	0.194	5.897	*0.023*
STM	0.239	0.031	0.900	0.353	0.256	0.059	1.736	0.201	0.217	0.040	1.118	0.302	0.265	0.021	0.632	0.435
Attention-Executive	0.241	0.002	0.053	0.820	0.256	0.000	0.000	0.991	0.219	0.002	0.061	0.807	0.274	0.009	0.252	0.621

Table 4-29. Higher- and lower-performance group hierarchical regression for the dot-cross task (where the verbal component entry is last).

	HP group															
	CAT_LH				CAT_RH				COORD_LH				COORD_RH			
Model 9	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*
Age + NART	0.027	0.027	0.339	0.716	0.055	0.055	0.693	0.510	0.009	0.009	0.109	0.897	0.036	0.036	0.444	0.646
Attention-Executive	0.057	0.030	0.728	0.402	0.071	0.016	0.400	0.533	0.009	0.000	0.000	0.953	0.044	0.008	0.193	0.664
STM	0.120	0.063	1.574	0.223	0.195	0.124	3.379	0.080	0.139	0.130	0.130	0.082	0.176	0.132	3.521	0.074
Verbal	0.125	0.004	0.104	0.750	0.215	0.020	0.541	0.470	0.144	0.005	0.005	0.719	0.181	0.006	0.141	0.711
	LP group															
Age + NART	0.033	0.033	0.415	0.665	0.001	0.001	0.016	0.984	0.022	0.022	0.268	0.767	0.051	0.051	0.640	0.536
Attention-Executive	0.034	0.000	0.001	0.972	0.003	0.002	0.050	0.825	0.029	0.007	0.172	0.682	0.067	0.016	0.396	0.536
STM	0.077	0.043	1.036	0.320	0.077	0.073	1.746	0.200	0.077	0.048	1.153	0.294	0.094	0.027	0.656	0.427
Verbal	0.241	0.164	4.532	*0.045*	0.256	0.179	5.057	*0.035*	0.219	0.141	3.802	*0.065*	0.274	0.180	5.221	*0.033*

Since significant impact of the verbal component has been found in the LP group, the hierarchical regression was carried out using the three cognitive components in the next step to observe the proportion of variance explained by each of the variables. This method investigates whether the significant finding of the verbal component was the consequence of cumulative variance from the background variables (i.e. age, NART score). Model 10 (Table 4-30) examined the proportion of variance explained by the cognitive components with the verbal component allocated at the top of the model, whereas Model 11 adopted a different order where the verbal component was placed last and the attention-executive component was placed firstly (Table 4-31). The result showed that regardless of the position where the verbal component is located, the amount of variance explained by the verbal component was significant for the visuo-spatial judgments. This consistent finding suggests that verbal ability can be used to predict the performance of the LP group when processing the dot-cross task. When the order of the attention-executive and STM component entry was reversed in Model 10 and Model 11, the results remained similar. Neither attention-executive functions nor STM ability could predict the task performance for the HP and LP group.

Table 4-30. Hierarchical regression for the HP and LP group with the three cognitive composites where the verbal component entry is first.

	HP group															
	CAT_LH				CAT_RH				COORD_LH				COORD_RH			
Model 10	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*
Verbal	0.000	0.000	0.006	0.940	0.000	0.000	0.006	0.938	0.001	0.001	0.021	0.885	0.003	0.003	0.064	0.802
Attention-executive	0.048	0.048	1.209	0.282	0.017	0.017	0.407	0.530	0.002	0.001	0.016	0.901	0.007	0.004	0.107	0.747
STM	0.104	0.056	1.429	0.244	0.111	0.094	2.442	0.132	0.114	0.113	2.924	0.101	0.104	0.097	2.477	0.129
	LP group															
Verbal	0.152	0.152	4.475	*0.045*	0.193	0.193	5.969	*0.022*	0.163	0.163	4.863	*0.037*	0.215	0.215	6.850	*0.015*
Attention-executive	0.154	0.002	0.048	0.829	0.193	0.000	0.006	0.937	0.170	0.007	0.204	0.656	0.235	0.020	0.628	0.436
STM	0.216	0.062	1.830	0.189	0.250	0.057	1.737	0.200	0.218	0.048	1.405	0.248	0.264	0.029	0.898	0.353

Table 4-31. Hierarchical regression for the HP and LP group with the three cognitive components where the verbal component entry is last.

	HP group															
	CAT_LH				CAT_RH				COORD_LH				COORD_RH			
Model 11	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*	R^2	R^2 change	F for R^2 Change	*p*
Attention-executive	0.048	0.048	1.266	0.271	0.016	0.016	0.415	0.526	0.001	0.001	0.019	0.892	0.005	0.005	0.123	0.729
STM	0.100	0.052	1.391	0.250	0.101	0.085	2.263	0.146	0.111	0.110	2.969	0.098	0.102	0.098	2.608	0.119
Verbal	0.104	0.004	0.090	0.766	0.111	0.010	0.264	0.612	0.114	0.003	0.087	0.770	0.104	0.001	0.029	0.866
	LP group															
Attention-executive	0.000	0.000	0.001	0.979	0.003	0.003	0.075	0.786	0.015	0.015	0.368	0.550	0.034	0.034	0.869	0.360
STM	0.069	0.069	1.771	0.196	0.066	0.063	1.631	0.214	0.068	0.053	1.375	0.252	0.067	0.034	0.870	0.360
Verbal	0.216	0.147	4.316	*0.049*	0.250	0.183	5.615	*0.027*	0.218	0.150	4.403	*0.047*	0.264	0.196	6.137	*0.021*

4.2.4 Summary and discussion of Experiment 5

The neuropsychological study was designed to observe possible different mechanisms for the higher- and lower-performance group in order to look for evidence in line with either the cognitive scaffolding (STAC) or for the dedifferentiation theory. Similar to the findings with the young group, both of the middle-aged and older groups showed a categorical advantage effect in the CATCOORD task. However, performance did not differ significantly between these two groups. Middle-aged participants only performed significantly better than older adults when objects' spatial change was apparent e.g. a categorical change combined with a large shift. These significant differences were found for accuracy results only. For the dot-cross task, the hemispheric effect for categorical and coordinate spatial relations only emerged in the older group. The middle-aged group showed the hemispheric effect at the trend level. Once again, there was no significant group difference between the middle-aged and the older group. The similar performance between the middle-aged and the older group in both of these tasks suggests that visuo-spatial cognitive function was relatively preserved in the older participants.

A series of standard neuropsychological tests were introduced to examine general cognitive ability in the recruited population. First of all, the performance between the middle-aged and the older group was compared. The results showed that the older group did not differ from the middle-aged greatly in most of the tasks apart from VPT, a spatial pattern memory test. The older participants were then divided into OH and the OL groups according to their mean Z scores. The OL group showed significantly worse performance than the OH group on all measures apart from VPT. In order to observe possible different cognitive profiles between the two groups, correlations among the neuropsychological tests were carried out for the OH and the OL group. The OH group showed fewer correlations across different cognitive tasks than the OL group. The results suggest that the cognitive profiles adopted by the two groups were different. In addition, comparison of the three groups (i.e. middle-aged, OH, and OL) showed significant group difference on all of the tasks. Specifically, the OL group performed worse while the performance for the middle-aged and the OH group did not differ significantly on most of the neuropsychological tasks. In some tasks, such as the digit span memory task (forward and backward), the OH group even performed better than the middle-aged group. These findings contradict one of the predictions; that the middle-aged group would show better cognitive performance than the older groups. As the current study aims to explore possible difference between people with good/preserved cognitive ability and those with poor cognitive ability, the exploratory analysis was adjusted to investigate the issue. The exploratory analysis mixed both middle-aged and older adults (age below 70 years old) and re-divided them into HP and LP group. The result showed similar cognitive profiles to the OH and OL group; the HP group showed less interconnectedness across different cognitive tasks whereas the LP group linked more cognitive abilities while performing tasks. The finding suggests that ability, rather than age, may be a more influential factor affecting cognitive performance in ageing.

PCA extracts three principal components, attention-executive component, verbal component, and STM component, from the neuropsychological battery. When utilising the cognitive components in the correlation analysis with the visuo-spatial STM tasks, the results indicated that there was no specific association between the cognitive components and the performance of the CATCOORD task or the dot-cross task. When performing correlations within the HP and LP groups, the LP group showed a significant correlation between the verbal component and the performance for the dot-cross task. However, none of the cognitive components associated with the performance for the CATCOORD task.

The three cognitive components were also applied to hierarchical multiple regression analysis in order to explore the underlying cognitive profiles for all participants when performing the two visuo-spatial tasks as well as for the HP and LP groups. The background variables, age and NART, explained the significant proportion of variance for the coordinate performance in the CATCOORD task. When performing the regression for the HP and LP groups, the background variables could estimate the coordinate performance in the HP group. In particular, NART score was a more influential predictor for the task performance than age. However, none of the cognitive composites could predict the performance of the HP and LP group on the CATCOORD task. The results of hierarchical regression analysis with the dot-cross task indicate that the cognitive ability (i.e. the HP and LP group) could be a predictor for the coordinate performance, even after the variance of the background variables and the cognitive components have been accounted for. The verbal component showed a trend of significance in explaining the variance for the task performance after the variance from the background variables and cognitive ability was accounted for. However, the only significant finding occurred when coordinate changes were presented on the right hemisphere. While performing the regression for the HP and LP groups, the verbal component consistently explained the significant proportion of variance for the task performance in the LP group. The amount of variance explained by the STM component was significant when categorical changes were presented on the right hemisphere in the HP group, but this may be a coincidence. Overall, verbal ability is able to adequately predict the performance on a visuo-spatial memory task (i.e. the dot-cross task) in the LP group but not the HP group. None of the other cognitive components could predict performance for either group.

The current study did not show a linear decline trend from middle-aged to older participants. In fact, some of the OH participants showed better cognitive performance than the middle-aged participants. This is likely due to sampling as older participants were recruited via sports clubs, IoN volunteer newsletter, Newcastle Elders Council, and age UK. It is speculated that older adults who were socially active, e.g. with social-economic advantage, and with better cognitive performance were more willing to participate the study (Rabbitt, Lunn, Ibrahim, & McInnes, 2009). Although age had an impact on performance of psychomotor speed and spatial ability, its influence on executive functions and verbal ability was limited. This agrees with the study of Park et al. (2001a) who demonstrated that as people become older, their psychomotor speed and spatial ability is likely to be affected. The predicted verbal IQ influenced a different aspect of cognitive system, attention and executive functions, in older adults. While age and NART have been demonstrated to have an impact on some cognitive functions, the influence from years of formal education was minimal. Therefore, only age and NART were included as background variables in hierarchical multiple regression analysis.

When comparing the performance of the CATCOORD and the dot-cross task between middle-aged and older participants, they showed similar performance patterns. Hence age was not a critical factor in the performance of either task. The consistent finding of the categorical advantage effect in the CATCOORD task has further extended the findings from the previous study (Dent, 2009). The result suggests that the broader, abstract visuo-spatial relations are primary in visuo-spatial representation regardless of age. As for the dot-cross task, the older group showed a trend of slower response time than the middle-aged group, but more importantly, the lateralisation hemispheric effect was found in accuracy of performance. This result supports the previous finding in which the underlying spatial representations remain consistent with age (Meadmore et al., 2009). The RT result showed a hint of the lateralisation effect by demonstrating more rapid responses for categorical spatial relations when the stimuli were presented on the left hemisphere. In addition, older participants also demonstrated slightly longer reaction times than the middle-aged group, which is consistent with the previous work (Meadmore et al., 2009). The finding that the older group revealed the lateralisation effect for the dot-cross task only in accuracy could be attributed to the difficulty of the visuo-spatial memory task. Older participants found the task difficult enough that the lateralisation effect was revealed in accuracy, whereas the young participants demonstrated the lateralisation effect in the variation of reaction time. More trials may lead to the interaction of the spatial relations and the hemispheres in RT reaching a significant level. The fact that hemispheric lateralisation effects did not emerge in the middle-aged group may be due to the smaller sample size/larger variation.

Participants with higher cognitive ability showed fewer correlations between different cognitive resources when performing cognitive tasks, while those with poorer cognitive ability showed more correlations among various cognitive resources. This finding seems to support the dedifferentiation hypothesis. The widespread cognitive profile seems to associate with cognitive ability, irrespective of age. It seems that the lower performance group shows lack of suppression of irrelevant information and these participants tended to include any available resources non-selectively. Gazzaley et al. (2005) conducted two experiments with fMRI to observe whether older participants are able to enhance the relevant information for task goals as well as suppress irrelevant information. The results showed that healthy older adults could not suppress irrelevant information yet their ability of selective attention for relevant information was relatively preserved. In addition, older participants who showed poor memory performance were less able to inhibit irrelevant information than those who have good memory performance. Thus they concluded that impaired suppression of to-be-ignored information is correlated with poor short-term memory performance in healthy ageing. Other studies along these lines propose that deficits in selecting attention for relevant information and suppressing for irrelevant information are the two key components which cause cognitive decline in ageing (de Fockert, 2005; Gazzaley et al., 2005; Logan et al., 2002). The reason more cognitive correlates were found in the LP group and additional verbal resources were used when performing a visuo-spatial memory task may be related to their impairment in inhibiting intrusions from task-irrelevant information. The HP group, on the other hand, demonstrated few correlations across different cognitive abilities, which may be explained by their better preserved ability to suppress irrelevant information.

The current study with older participants has demonstrated that categorical and coordinate visuo-spatial relations are not affected by age. The categorical spatial representation retains its dominant role in visuo-spatial process in ageing. Lower cognitive function participants show a more homogenous profile when cognitive resources are reduced, which is in line with the notion of dedifferentiation. People who manage to preserve the ability to inhibit irrelevant information and to focus on relevant information may be able to maintain their cognitive ability in older age. The current study only examines the ageing hypotheses through behavioural performance. The underlying mechanism in the ageing brain is unclear. If the behaviourally broader cognitive profile found in the LP group also appears in the brain activity, then the dedifferentiation hypothesis is more likely to be supported. However, if a broad neural network is found in the ageing brain in the HP group, the result may suggest an underlying cognitive scaffolding mechanism, supporting the behavioural performance of people who manage to maintain cognitive ability in older age. The following study will incorporate a neuroimaging technique to observe the correspondent neural networks in older adults when performing the dot-cross task. Neuroimaging results are then associated with neuropsychological/behavioural performance in order to explore the different brain activity recruited by older adults with better vs. poorer cognitive performance.

4.3 Experiment 6: Neuroimaging study in older adults

4.3.1 Introduction

The neuropsychological study aimed to observe possible different behavioural patterns between the higher- and lower-cognitive performance groups. The results showed a broader cognitive profile in participants with poor cognitive ability than those with better cognitive ability. This neuroimaging study is designed to examine the underlying neural mechanism of spatial ability in the ageing brain. Only the dot-cross task was examined because it is a more suitable task to reveal the difference between categorical and coordinate spatial representations. As described in Experiment 3 (see section 3.2.3) and Experiment 5 (see section 4.2.3.1.2), a hemispheric lateralisation effect was consistently found in both young and older participants in behavioural experiments. The middle frontal region was activated when processing coordinate spatial judgments but not categorical judgments in the young group tested with fMRI (see Experiment 4, section 3.3.3.2). This difference between the two spatial processes in the young group indicates that coordinate spatial judgments require additional attention and/or executive resources compared to categorical spatial judgments. The current study recruited participants from the older group only (i.e. age above 60). An identical experiment procedure to that followed with the young group was applied in the older group, which enables the results from the two groups to be compared directly. In addition, older participants were separated into higher- and lower-performance groups (OH and OL) (see Experiment 5, section 4.2.3.4) so that the neural networks between the three groups (i.e. young, OH, and OL) could be compared. Note that middle-aged participants were not studied with fMRI because they were a reference group, to examine whether the results from the CATCOORD task and the dot-cross task found in the young could be tested in a more general population. According to the scaffolding hypothesis, the OH group is predicted to show more brain activation in frontal areas due to extra recruitment of central executive functions and/or attention. Alternatively, they may show a broad neural network, e.g. a network involving posterior to frontal regions or bilateral activations, during the visuo-spatial process. It was also predicted that OL participants may show weaker activation in the frontal area or restricted connections between different brain regions when processing the dot-cross task.

4.3.2 Methods

4.3.2.1 Participants

Thirty-eight eligible participants from the old group were recruited to the fMRI study. Twenty-one females and 17 males completed the study. However, 5 of the participants had to be excluded from the analysis due to extremely poor performance in accuracy, excessive head movements or imaging technical problems. Eighteen females and 15 males (mean age=66.18, SD=5.83) were included in the final analysis. All participants were right-handed and had normal or corrected-to-normal vision. Participants received £20 after they had completed the neuroimaging study. The research was approved by the Faculty of Medical Sciences Ethics Committee in Newcastle University.

4.3.2.2 Design and procedure

The participant information sheet and consent form were presented to participants before the study. The study design and procedure were identical to the young group (ref. Exp.4, section 3.3.2.2) except a longer reaction time was allowed for older adults (3000ms). Participants underwent 176 trials during the practice session outside of the scanner. In the scanner, 50 trials were provided to the participants prior to the real experiment session to acclimatise them to the experimental procedure and mode of response. Participants then underwent another 176 trials during the scan session. Categorical and coordinate judgment trials were all randomised. The duration of the scan session was 25 minutes. Both accuracy and reaction times were recorded via Presentation® software (version 16.2, www.neurobs.com)

4.3.2.3 Data analysis

4.3.2.3.1 Behavioural data

A two-way, 2 (categorical change vs. coordinate change) x 2 (LVF/RH vs. RVF/LH), within subject repeated-measure ANOVA was utilised to analyse accuracy and reaction time for the performance during the scan session.

4.3.2.3.2 Imaging acquisition and data analysis

The imaging acquisition was adopted from the same MRI system as described previously (see Exp.4).

Imaging processing and statistical analysis were performed with SPM8 software (www.fil.ion.ucl.ac.uk). The pre-processing procedure followed the same process as the previous study in order to normalise neuroanatomy images.

A flexible factorial design was applied in the second level statistical analysis; only scans for correctly answered trials were included in the analysis. Cluster activations, relative to activity at fixation baseline, in the "categorical-correct" and "coordinate-correct" conditions were deemed significant if a $p<0.05$ (Family-Wise Error correction) was achieved. Similarly, contrast images (e.g. CAT>COORD) were created to compare activity in the "categorical-correct" and "coordinate-correct" conditions; significance was determined if $p<0.05$ (FWE). An average brain image from the current sample was created in order to interpret cluster regions more accurately in the ageing brain. The Automatic Anatomical Labelling toolbox for SPM8 was used to identify areas of cluster activation.

4.3.3 Results

4.3.3.1 Behavioural results

Accuracy of performance is presented in Figure 4-16. Similar to the previous findings, the categorical advantage effect was found in the current study ($F(1,32)=28.57$, $p<.001$). The categorical spatial judgments (mean=87.9%) were performed better than the coordinate judgements (mean=82.2%). An interaction between the spatial relations and the hemispheres was found at the trend level ($F(1,32)=3.30$, $p=0.078$). The left hemisphere (mean=89.1%) performed better when judging categorical spatial relations than the right hemisphere (mean=86.7%) and the right hemisphere (mean=82.5%) showed slightly better performance in judging coordinate changes than the left hemisphere (mean=81.9%). The hemispheric effects were not significant ($F<1$).

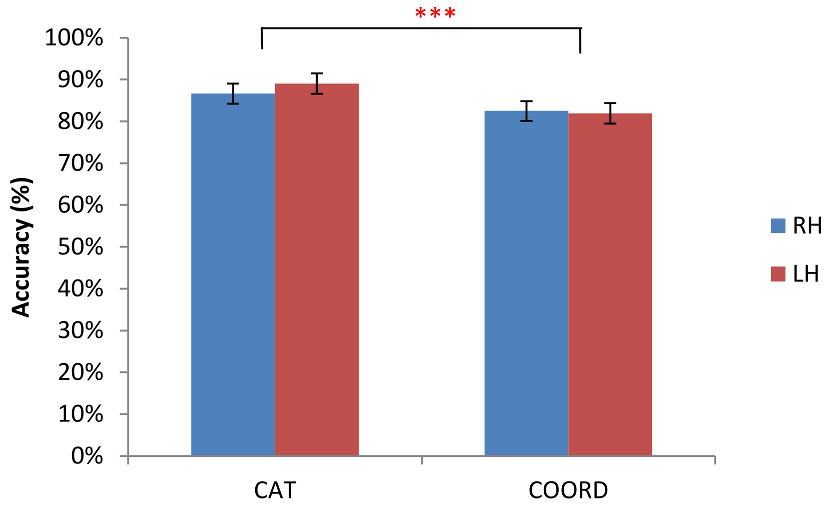


Figure 4-16. Accuracy of the dot-cross task during the scan session (n=33). '***' means $p<0.001$.

Reaction times for the two spatial relations judgments are depicted in Figure 4-17. There were no main effects for spatial relations ($F(1,32)=2.59$, $p=0.117$) or hemispheric effects ($F<1$). The interaction between the spatial relations and hemisphere was also not significant ($F(1,32)=3.01$, $p=0.092$).

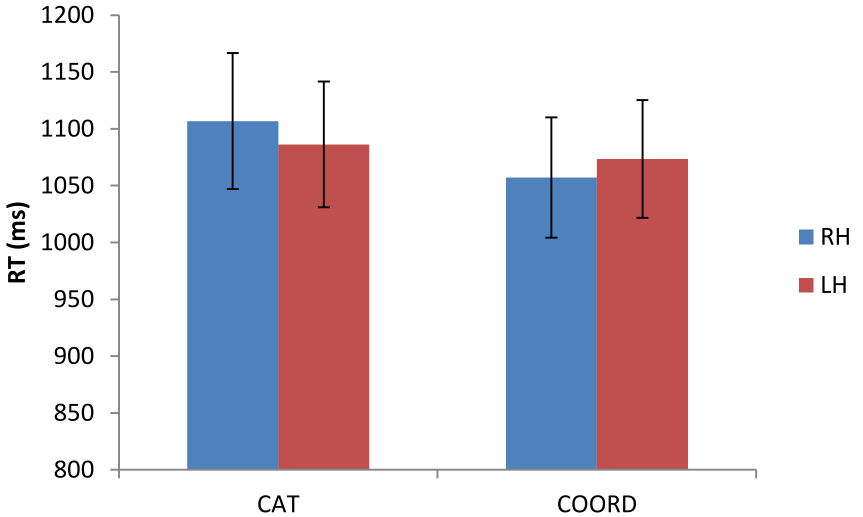


Figure 4-17. Reaction times for the dot-cross task during the scan session (n=33).

Overall, the behavioural performance inside of the scanner was similar to the results from outside of the scanner. A similar result pattern was found in which faster and more accurate responses for categorical spatial judgments were found when stimuli presentation was to the left hemisphere, while the right hemisphere showed an advantage in processing coordinate spatial relations.

4.3.3.2 Neuroimaging results

Figure 4-18 and Table 4-32 show the results of group analysis for the imaging data in old participants (p<0.05 after correcting for FWE across the whole brain). Similar to the young group (ref. Exp.4), older adults showed bilateral activations of the whole brain when processing both categorical and coordinate spatial judgments. The activation pattern between the two spatial processes was similar to each other (Figure 4-18). Table 4-32 displays top clusters for the contrasts of CAT>baseline and COORD >baseline. Left frontal regions showed greater activations than right frontal regions during both types of visuo-spatial processing. In addition, middle occipital gyrus revealed greater activations during coordinate spatial judgments.

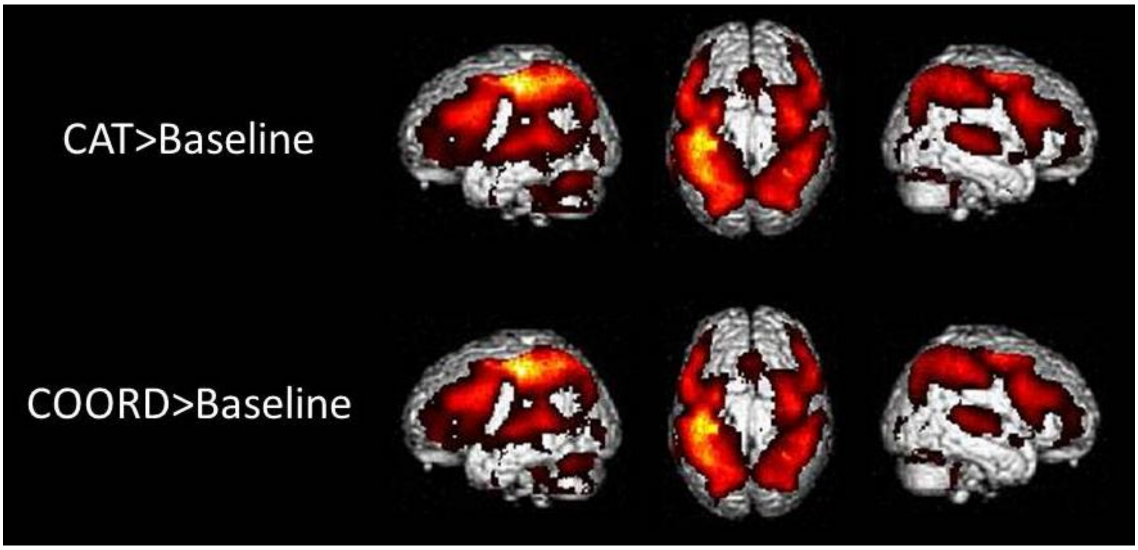


Figure 4-18. Contrasts of categorical or coordinate condition vs. baseline (FWE correction, p<0.05).

Table 4-32. Top clusters for the whole brain analysis for the CAT>Baseline and COORD>Baseline contrasts (FWE corrections, p<0.05, k≥10).

Region	Local peak	Cluster (voxels)	t-value (peak)	Mean Z (peak)	MNI mm (x,y,z)
		CAT>Baseline			
Frontal	L precentral gyrus	63122	123.59	Inf.	(-36,-20,52)
	L postcentral gyrus		84.40	Inf.	(-42,-34,50)
	L middle frontal gyrus		84.25	Inf.	(-28,2,60)
	L precentral gyrus	54	17.95	Inf.	(-44,-4,40)
	L fusiform gyrus		6.61	5.99	(-42,-4,30)
Others	R cerebellar tonsil	34	10.34	Inf.	(2,-50,-50)
		COORD>Baseline			
Frontal	L precentral gyrus	52070	129.76	Inf.	(-36,-20,52)
	L middle frontal gyrus		83.14	Inf.	(-28,-2,60)
	L sub-gyral		80.55	Inf.	(-22,-8,58)
	R extra-nuclear	120	10.99	Inf.	(42,6,-10)
	R inferior frontal gyrus		6.77	6.10	(52,18,-6)
	L precentral gyrus	47	17.88	Inf.	(-44,-4,40)
Occipital	R middle occipital gyrus	79	10.69	Inf.	(28,-84,6)
	R lingual gyrus		8.99	7.63	(22,-92,-6)
Others	R inferior semi-lunar lobule	5867	64.73	Inf.	(10,-74,-50)
	L inferior semi-lunar lobule		33.12	Inf.	(-8,-76,-48)
	Culmen	114	11.74	Inf.	(0,-46,-4)
	R cerebellum tonsil	15	7.89	6.91	(2,-50,-50)

To compare the different brain regions involved in categorical and coordinate spatial judgments, the signal acquired during the response phase, i.e. the duration between the end of stimuli presentation and the response button being pressed, in the categorical condition was contrasted with the coordinate condition (CAT>COORD). The categorical condition showed greater neural activation than the coordinate condition in the direct contrast, particularly in posterior parietal regions as well as frontal regions. Posterior regions such as precuneus, supermarginal gyrus, and middle temporal gyrus were activated bilaterally as well as middle frontal gyrus in frontal cortex (Figure 4-19 and Table 4-33). The right parietal-temporal region also showed greater neural activity in the categorical condition than the coordinate condition. However, no significant cluster was found in the reversed contrast for the conditions (COORD>CAT).

Similarly to the findings in young people, the categorical and coordinate spatial processing revealed bilateral brain activity in the ageing brain. In addition, categorical spatial judgments required greater activation than the coordinate judgments, especially in the posterior parietal-temporal region and middle-frontal area.

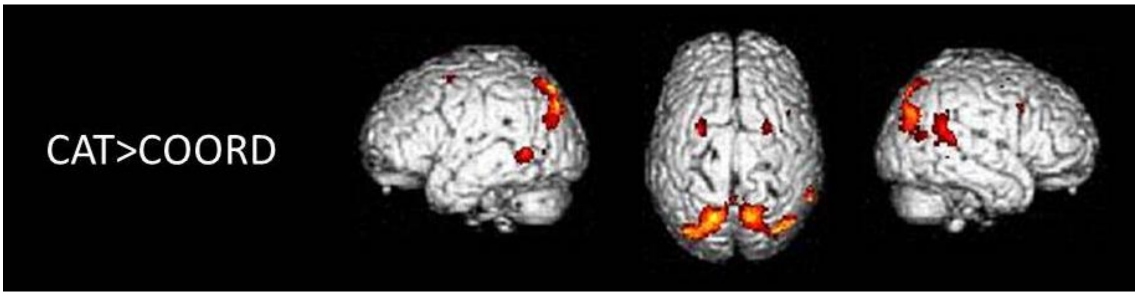


Figure 4-19. Contrast of the categorical>coordinate condition (FWE correction, $p<0.05$). N.B. *There were no significant clusters found in the reverse contrast (COORD>CAT).*

Table 4-33. Top clusters for the whole brain analysis for the CAT>COORD contrast (FWE correction, $p<0.05$, $k \geq 10$).

CAT>COORD

Region	Local peak	Cluster (voxels)	*t*-value (peak)	Mean Z (peak)	MNI mm (x,y,z)
Parietal-temporal	L precuneus	1700	7.49	6.63	(-16,-74,50)
	R angular gyrus		7.38	6.55	(36,-78,32)
	R superior parietal lobule		7.37	6.54	(14,-66,54)
	R supermarginal gyrus	217	6.30	5.75	(58,-50,24)
	R superior temporal gyrus		5.86	5.41	(58,-44,18)
	L middle temporal gyrus	101	6.39	5.82	(-62,-54,-2)
Frontal	L sub-gyral	93	6.54	5.93	(-24,-2,56)
	R sub-gyral	41	5.61	5.21	(26,0,52)
	R middle frontal gyrus	36	5.93	5.46	(36,12,34)
	R sub-gyral	21	5.72	5.29	(18,-60,24)

The reverse contrast for task difference (COORD>CAT) showed no significant clusters.

4.3.3.3 Exploratory analyses

This section correlates cognitive behavioural performance (derived from the previous neuropsychological battery) with the neural activations observed in the current study in order to explore possible differences between higher and lower cognitive function participants. Participants were separated into the old-higher (OH) and old-lower (OL) groups in accordance with their cognitive performance on the neuropsychological battery rather than performance on the dot-cross task. In fact, the OH and OL group did not show significant difference in accuracy ($F<1$) and RT ($F(1,31)=1.17$, $p=0.289$) on the dot-cross task.

There was a significant effect of age ($F(2,48)=317.28$, $p<0.001$); the young group (mean age=27.67) was significantly younger than the OH group (mean age=64.06) and the OL group (mean age=68.44). The OH group was also significantly younger than the OL group ($t(31)=-2.29$, $p=0.029$).

The following section focuses on comparisons between the young, OH and OL groups and explores different underlying neural networks in the three groups. The scaffolding hypothesis will be supported if OH participants show greater and/or broader activations than the young and the OL group. However, if a broader neural network is found in the OL group than the OH and young group, the dedifferentiation hypothesis may be supported.

4.3.3.3.1 Behavioural comparison (Young vs. OH vs. OL)

The dot-cross neuroimaging studies for young participants (Experiment 4) and older participants (Experiment 6) were able to be directly compared to each other given the identical study procedure between the two studies. A 2 (Spatial relations) × 2 (Hemisphere) × 3 (Group) mixed design ANOVA was carried out, where the spatial relations (CAT and COORD) and hemispheres (LH and RH) were within-subjects factors and the groups (Young and OH and OL) was set as a between-subjects factor. The accuracy results of the three groups were similar: Young=88.6%, OH=83.6%, OL=86.6% ($F<1$) (Figure 4-20). A main effect of spatial relations was found ($F(1,48)=26.90$, $p<0.001$). Categorical spatial judgments showed better memory performance than coordinate spatial judgements (89.0% vs. 83.5%). However, neither a main effect of the hemispheres ($F<1$) nor the interaction was found ($F(1,48)=1.40$, $p=0.242$). The three-way interaction between spatial relations, hemispheres and groups was also not significant ($F<1$). Age did not covary with the participants' performance ($F(1,47)=1.41$, $p=0.240$), which confirmed the previous finding that the categorical advantage effect appears throughout life span.

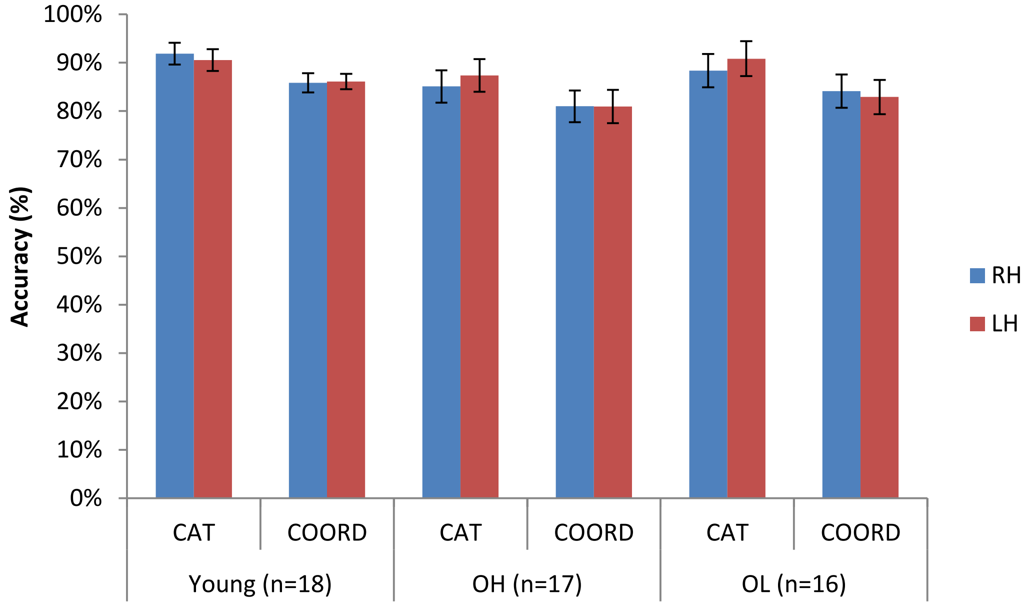


Figure 4-20. Accuracy between the young, the old-higher and the old-lower performance group.

Figure 4-21 presents the reaction times for the three groups. A main effect of group was found: Young=834ms, OH=1025ms, and OL=1140ms ($F(2,48)=5.91$, $p=0.005$). Post hoc analysis indicated that the young group responded much faster than the OH and the OL group whilst the OH and the OL group did not differ from each other. A significant interaction between the spatial relations and the hemispheres was also found ($F(1,48)=6.95$, $p=0.011$). Participants were faster when coordinate change trials were presented to the RH than the LH ($t(50)=-2.22$, $p=0.031$). Responses were faster for coordinate judgments than categorical judgments when the stimuli were presented to RH ($t(50)=2.22$, $p=0.031$). The main effects of the spatial relations ($F(1,48)=1.27$, $p=0.265$), the hemispheres ($F<1$) and the three-way interaction between groups, spatial relations, and hemispheres ($F<1$) were all non-significant. Age was not a significant covariate ($F(1,48)=1.46$, $p=0.233$). Performance of the three groups was not affected by age. The group difference, which emerged in RT results, confirms the previous finding that RT is a better indicator to observe the hemispheric lateralisation effect for visuo-spatial processing in the dot-cross task. An advantage of the right hemisphere for coordinate spatial processing was found.

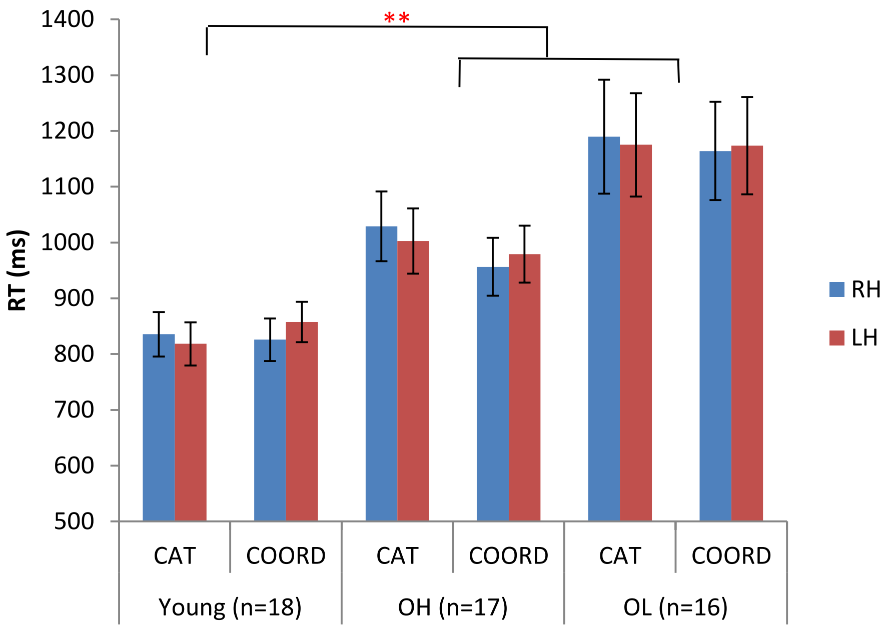


Figure 4-21. Reaction times for the young, old-higher and old-lower performance group.

4.3.3.3.2 Neuroimaging comparison (Young vs. OH vs. OL)

Bilateral cerebral activation was found in all three groups when processing the visuo-spatial relations task. By visually viewing Figure 4-22, the young group shows fewer regions activated during the visuo-spatial process than either of the older groups. Within the older groups, a broader neural network was presented in the OH than OL group. Table 4-34 depicts direct contrasts between the young and the OH group, and the young and the OL group. The young group showed less neural activation in the precuneus and the fusiform gyrus than the older groups. However, there was no significant greater activation found in the young than the older groups. The OH group presented greater activations in some frontal regions than the OL group yet the results from cluster-level analysis were not significant (see Figure 4-22 and Table 4-35). An analysis including age as a covariate showed similar results.

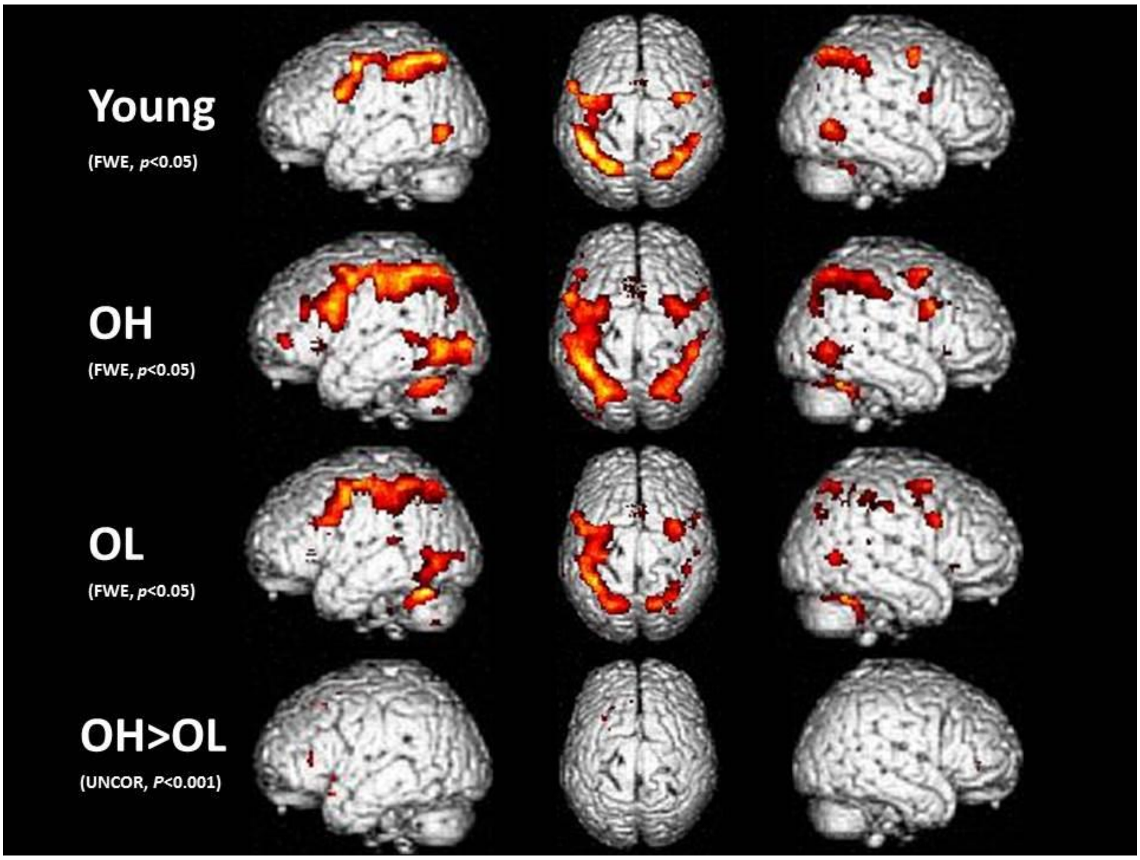


Figure 4-22. Render brain images represent the whole brain activations during the task for young, OH, OL and the contrast between the OH and OL group. Note that the results of the young, OH and OL are presented with FWE correction, p<0.05. The OH>OL contrast is set with uncorrected data analysis, $p<0.001$, $k\geq10$.

Table 4-34. Top clusters for the whole brain analysis for the Young<OH and Young<OL contrast (FWE correction, $p<0.05$).

Region	Local peak	Cluster (voxels)	*t*-value (peak)	Mean Z (peak)	MNI mm (x,y,z)
		Young<OH			
Parietal	R precuneus	39	6.09	5.21	(2,-46,46)
Temporal	L sub-gyral	176	7.22	5.91	(-30,-50,-14)
	L fusiform gyrus		5.71	4.97	(-38,-52,-22)
	R sub- gyral	59	6.48	5.46	(28,-54,-14)
		Young<OL			
Parietal	R precuneus	56	6.67	5.58	(2,-44,46)
	R precuneus	16	5.58	4.88	(4,-58,54)
Occipital	L fusiform gyrus	27	5.95	5.12	(-28,-52,-14)
Temporal	L fusiform gyrus	25	5.76	5.00	(-38,-52,-22)

There were no significant clusters found in the contrasts of Young>OH and Young>OL.

Table 4-35. Top clusters for the whole brain analysis for the OH>OL and the OL>OH contrast (uncorrected, p<0.001, k≥10).

Region	Local peak	Cluster (voxels)	*t*-value (peak)	Mean Z (peak)	MNI mm (x,y,z)
		OH>OL			
Frontal	L medial frontal gyrus	39	4.18	3.84	(-10,56,16)
	L superior frontal gyrus		3.35	3.15	(-18,56,18)
	R sub-gyral	33	4.57	4.14	(28,-6,36)
	L inferior frontal gyrus	14	3.62	3.39	(-38,14,-16)
	L insula	13	3.87	3.59	(-32,14,-2)
		OL>OH			
Limbic	L cingulate gyrus	29	4.03	3.72	(-12,2,48)

N.B. None of the clusters reached significant level in clusters-level analysis.

Figure 4-23 illustrates brain regions that were recruited in the three groups during the visuo-spatial process. All participants recruited bilateral frontal to parietal region to perform the dot-cross task.

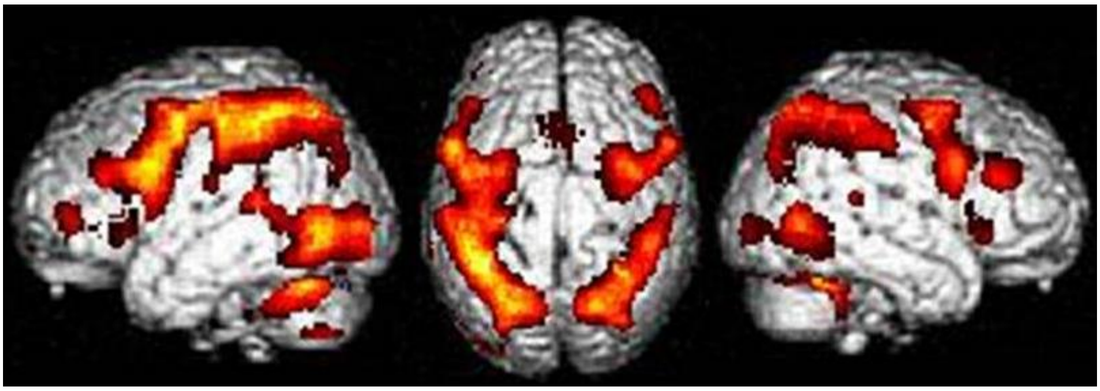


Figure 4-23. Brain regions that were activated in the young, OH, and OL group in the whole brain analysis (FWE correction, p<0.05).

An analysis which utilises RT as a modulator to investigate BOLD signal changes for longer response trials is applied in the following section. The methodology could observe regions that showed greater BOLD signal changes when processing difficult trials, i.e. longer reaction times. Young participants demonstrated greater frontal activity in coordinate but not categorical spatial processing with this analysis (see Experiment 4, section 3.3.4). The finding suggests that they recruited more attention/executive resources when performing difficult coordinate change trials. The following section applies the same analysis to observe if older adults utilise similar compensatory mechanisms and to further compare brain networks between the three groups.

The results of BOLD signal changes after modulation with response time among the three groups are reported in Figure 4-24. Similar to the findings in Experiment 4, frontal area showed greater BOLD signal changes when performing more difficult trials. The young group revealed the greatest BOLD signal changes in frontal region when globally viewing the neuroimaging results. In particular, the young group showed significantly greater BOLD signal changes in the middle frontal area, including middle frontal gyrus, anterior cingulate, and insula, than the OL group. The young and the OH group showed similar degree of BOLD signal changes in middle frontal region. None of the observed clusters reached a significant difference level in cluster-level analysis (see Table 4-36). Within the older groups, the OH group showed greater BOLD signal changes in frontal regions for more difficult trials than the OL group yet none of the observed clusters reached a significant level in cluster-level analysis. Moreover, greater BOLD signal changes in parietal-temporal-occipital region were found in the older groups than the young group when solving difficult trials, but again, none of the clusters was significant in cluster-level analysis (Table 4-36). The results were similar after covariate adjustment for age.

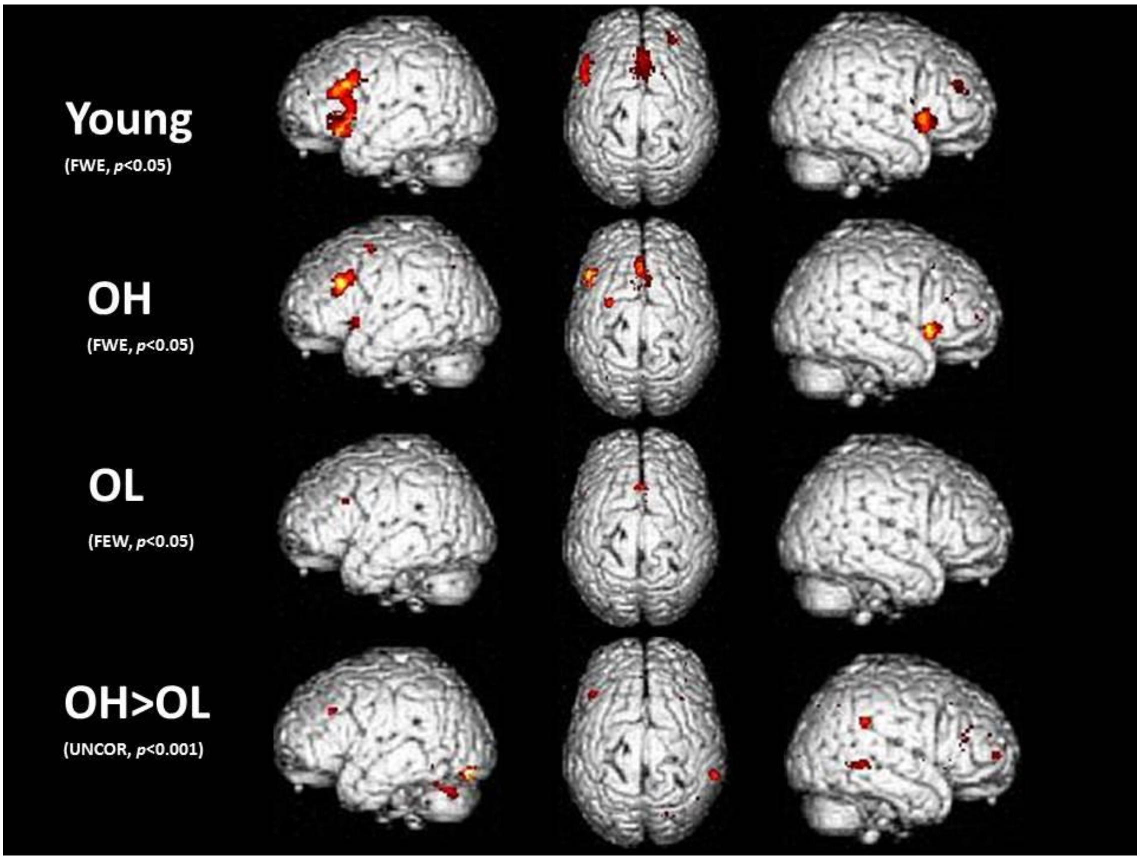


Figure 4-24. Render brain images present the associated BOLD signal changes with longer reaction times (i.e. RT modulation) for the young, OH, and OL group (FWE correction, $p<0.05$) and the contrast between the OH and OL group (uncorrected, $p<0.001$, $k \geq 10$).

Table 4-36. Top clusters from the comparisons of the young group and the older groups after the RT modulation (uncorrected, $p<0.001$, $k\geq10$).

Region	Local peak	Cluster (voxels)	t-value (peak)	Mean Z (peak)	MNI mm (x,y,z)
		Young>OH			
Frontal	Sub-gyral	41	4.94	4.42	(14,18,44)
	R medial frontal gyrus		3.63	3.40	(4,12,52)
	L precental gyrus	36	4.31	3.95	(-48,14,10)
	L inferior frontal gyrus	27	3.73	3.48	(-32,30,-4)
	L middle frontal gyrus	21	3.60	3.71	(-44,24,-12)
	L pecental gyrus	20	3.84	3.57	(-36,0,32)
	L precental gyrus		3.35	3.16	(-44,-2,36)
	R superior frontal gyrus	18	3.82	3.55	(26,40,22)
	R inferior frontal gyrus	15	3.84	3.57	(50,8,16)
	L cingulate gyrus	10	3.70	3.45	(-10,12,44)
		Young>OL			
Frontal	L precentral gyrus	824***	5.64	4.92	(-48,14,10)
	L middle frontal gyrus		4.98	4.45	(-46,26,22)
	L superior temporal gyrus		4.81	4.33	(-52,16,-12)
	R anterior cingulate	1355***	5.31	4.69	(4,22,28)
	R sub-gyral		5.16	4.58	(14,18,44)
	L medial frontal gyrus		4.95	4.43	(-6,14,52)
	R insula	867***	5.17	4.59	(34,18,6)
	R sub-gyral		4.90	4.39	(44,4,20)
	R precentral gyrus		4.67	4.22	(52,10,6)
	R middle frontal gyrus	113	4.63	4.19	(30,42,26)
	R superior frontal gyrus		3.72	3.47	(28,48,18)
	L sub-gyral	59	4.12	3.79	(-22,12,46)
	L medial frontal gyrus	51	3.91	3.62	(-18,40,28)
	L superior frontal gyrus		3.72	3.47	(-22,48,20)
	L precentral gyrus	51	4.23	3.88	(-38,0,30)
	L inferior frontal gyrus	36	3.87	3.59	(-50,10,36)
	R superior frontal gyrus	16	4.17	3.84	(20,12,56)
Parietal	R inferior parietal lobule	37	4.04	3.73	(64,-44,28)
Other	L claustrum	22	3.78	3.52	(-36,-20,-2)
		OH>Young			
Parietal-temporal-occipital	L precuneus	64	4.07	3.75	(-12,-56,56)
	R precuneus	21	3.77	3.51	(12,-60,60)
	R middle occipital gyrus	61	4.43	4.03	(36,-70,2)
	L superior temporal gyrus		3.50	3.29	(-36,-38,6)
	R cuneus	12	3.73	3.48	(22,-78,4)
Frontal	R precentral gyrus	27	3.75	3.50	(28,-14,60)
Other	L cerebellum	406***	4.65	4.20	(-40,-68,-28)
	R extra-nuclear	10	3.91	3.63	(30,-30,10)
	L extra-nuclear	22	3.77	3.51	(-26,-32,8)
		OL>Young			
Temporal-occipital	L extra-nuclear	74	4.40	4.01	(-26,-32,8)
	L superior temporal gyrus		3.71	3.46	(-36,-38,6)
	R transverse temporal gyrus	44	4.56	4.14	(32,-32,12)
	R extra-nuclear	43	4.27	3.91	(24,10,-8)
	R middle occipital gyrus	18	3.91	3.62	(36,-68,4)

N.B. The clusters that are not marked represent the results of cluster-level analysis that are not significant. "***" indicates cluster-level analysis is significant at $p<0.001$.

The image of the OH>OL contrast is depicted in Figure 4-24 and the following table presents details of the cluster-level comparison for the OH and OL group comparisons. The OH group showed greater BOLD signal changes in parahippocampal gyrus than the OL group. Nonetheless, none of the other observed clusters has reached a significant level in cluster-level analysis. There was no cluster found in the OL>OH contrast.

Table 4-37. Top clusters from the comparison of the OH group and the OL group after the RT modulation (uncorrected, $p<0.001$, $k\geq10$).

Region	Local peak	Cluster (voxels)	*t*-value (peak)	Mean Z (peak)	MNI mm (x,y,z)
		OH>OL			
Parietal-temporal-occipital	R supramarginal gyrus	43	3.93	3.64	(58,-40,32)
	R middle temporal gyrus	43	4.35	3.97	(66,-44,0)
	L middle occipital gyrus	*143*	4.33	3.96	(-26,-84,-16)
	L fusiform gyrus		3.98	3.68	(-36,-80,-18)
	L parahippocampal gyrus	182*	4.06	3.75	(-14,-40,-2)
Frontal	R middle frontal gyrus	25	3.80	3.53	(30,58,6)
	L middle frontal gyrus	25	3.71	3.46	(-40,26,32)
	R middle frontal gyrus	11	3.57	3.34	(42,34,18)
	Insula	10	3.57	3.34	(42,2,2)
Other	R cerebellum	22	3.69	3.44	(30,-44,-22)
	L cerebellum	65	4.13	3.80	(-42,-70,-34)

- *The reverse contrast (OL>OH) showed no significant clusters.*
- "*"represents the result that in cluster-level analysis is significant at $p<0.05$. *Italic* font represents the result of cluster-level analysis shows a marginal trend toward significance.

As some of the brain regions showed significant difference in the contrast of Young>OL and OH>OL (see Table 4-36 and Table 4-37), the section below attempts to observe differences in BOLD signal changes in the regions which were involved in processing difficult trials. Figure 4-25 depicts brain regions that showed greater BOLD signal changes when processing difficult trials in the young, OH, and OL group. Seven regions were selected and their local peaks (with sphere radius 5mm) were extracted to compare BOLD signal changes. The results of comparisons are displayed in Table 4-38. The young group showed greater BOLD signal changes than the OL group in the right cingulate gyrus (#1) when processing difficult trials. The difference of BOLD signal changes among the three groups showed a marginal trend toward significance in bilateral inferior frontal gyrus (LIFG: #2/#3 and RIFG: #4/#5). Post hoc comparison indicates that the significance was driven by greater BOLD signal changes in the young group than the OL group. There was no significant difference in BOLD signal changes among the three groups in the two posterior regions, the left inferior parietal lobule (#6) or the right precuneus (#7).

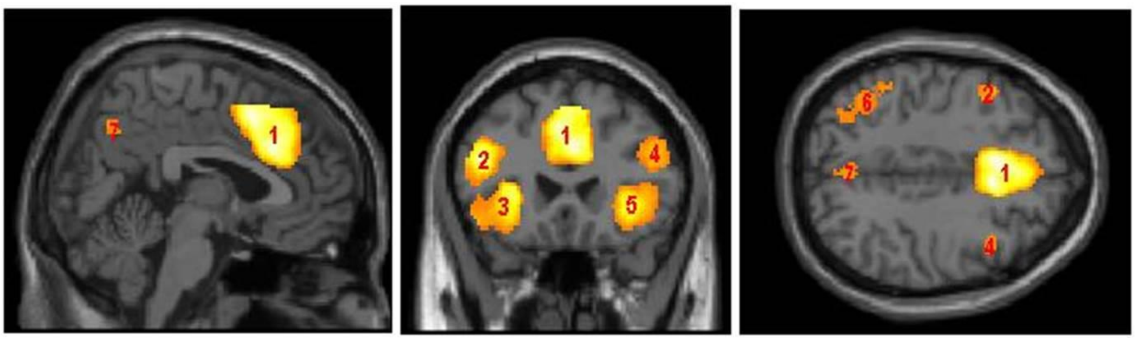


Figure 4-25. Brain regions showing greater BOLD signal changes in the young, OH, and OL group in long response time trials (FWE correction, *p*<0.05).

Table 4-38. Comparisons of BOLD signal changes between the three groups at the seven clusters (rf. Figure 4-25).

Region number	Local peak	MNI	*df*	*F*	*p*	Post hoc (LSD)
1	R cingulate gyrus	(4,24,32)	(2,48)	3.302	0.045	Young>OL*
2	L inferior frontal gyrus	(-48, 26, 24)	(2,48)	2.555	*0.088*	Young>OL*
3	L inferior frontal gyrus	(-40,18,-4)	(2,48)	1.707	0.192	-
4	R middle frontal gyrus	(46,28,28)	(2,48)	1.172	0.318	-
5	R inferior frontal gyrus	(42,18,-2)	(2,48)	3.091	*0.055*	Young>OL*
6	L inferior parietal lobule	(-36,-56,38)	(2,48)	0.743	0.481	-
7	R precuneus	(2,-66,44)	(2,48)	2.185	0.124	-

'*' indicates post hoc comparison is significant at the 0.05 level (2-taiiled).

Globally, the OH group showed a broader neural network than the other two groups in the whole brain analysis (see Figure 4-22). However, none of the regions showed significant difference in the OH>Young contrast (Table 4-34) and the OH>OL contrast (Table 4-35).

Similarly, the OH group seemed to demonstrate greater BOLD signal changes when processing difficult trials than the OL group in frontal and parietal-temporal regions yet only one of the clusters in parahippocampal gyrus showed significant difference in cluster-level analysis (Table 4-37). The following section demonstrates the relationship between brain activations, which are represented by the amount of voxels, and the results of response time. Only reaction times were reported here as they have demonstrated the group effect. Figure 4-26 displays combinations of brain activations and behavioural performance among the three groups. As it is only an overview to illustrate the relationship between behavioural performance and brain activations, no statistical analysis was carried out. In the basic analysis (i.e. whole brain analysis), there were fewer voxels involved in the young group than the older groups (7181 voxels) and their performance remained the best among the three groups (834ms). Within the older groups, more voxels were observed in the OH group than the OL group (19424 voxels vs. 12283 voxels). However, their performance in reaction times was not significantly different from each other (OH:1025ms vs. OL:1140ms, effect size=-0.38). When performing more difficult trials (where RT is adopted as a modulator for the analysis), the largest amount of voxels was observed in the young group (3610 voxels), followed by the OH (1514 voxels), and the OL group showed the least amount of voxels (241 voxels). Overall, with the best behavioural performance among the three groups, the young group utilised the least voxels when processing the dot-cross task and utilised the most voxels when processing difficult trials. The OH group utilised more voxels in the visuo-spatial memory task and also more voxels when processing difficult trials than the OL group, yet the reaction times of each group remained similar to each other.

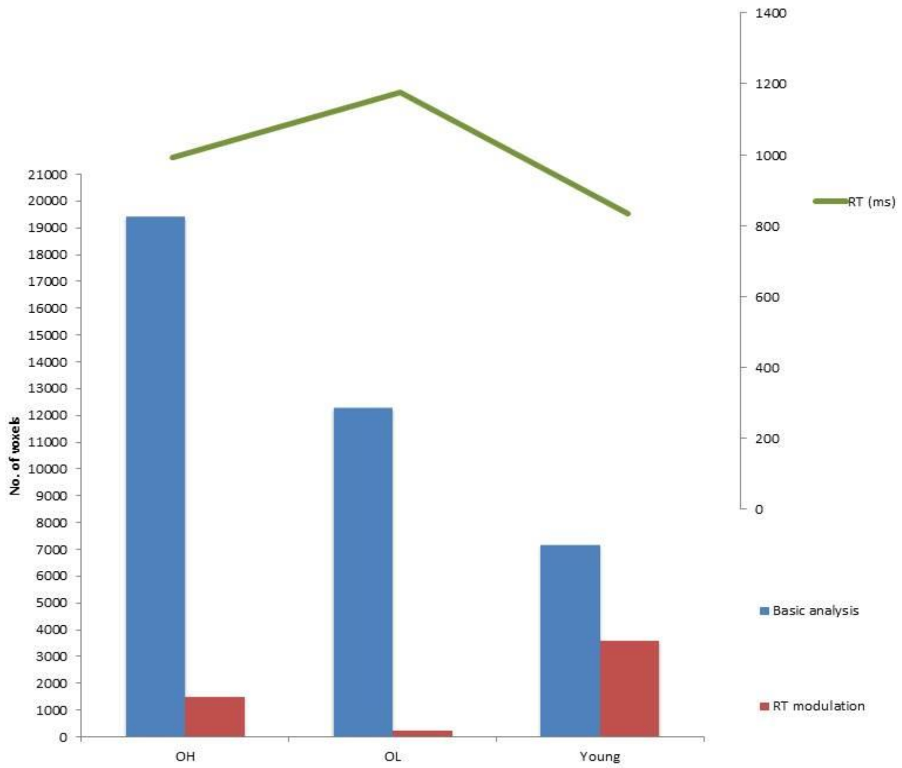


Figure 4-26. Combinations of brain activations in the two analyses (i.e. the basic analysis and the analysis with RT modulation) (FEW correction, *p*<0.05) and behavioural performance (RTs).

4.3.4 Summary and discussion of Experiment 6

The behavioural results in the current neuroimaging study showed a robust categorical advantage effect. The hemispheric lateralisation effect was found in the results of both accuracy and reaction times but only at trend level. As seen with young people, neuroimaging revealed bilateral activation when processing categorical and coordinate spatial relations in older adults. The categorical condition showed greater activation in posterior parietal-temporal region and middle-frontal area than the coordinate condition in the ageing brain. When comparing the three groups, reaction time was a behavioural index for distinguishing young and older participants. Although OH participants showed a trend of faster response time on trials than the OL group, the difference was not significant. An age effect was found, with the OL group being the oldest among the three groups. However, the slower reaction time observed in the OL group was not associated with age but with a poor cognitive profile. When comparing neuroimaging results, the young group recruited the least brain areas to perform the task. Specifically, young participants showed less neural activity in parietal-temporal regions than older participants. The OH group globally presented a broader neural network than the OL group. However, there was no significant finding in the direct contrast. When performing difficult trials, frontal cortex showed greater BOLD signal changes than other regions among the three groups. By globally viewing the neuroimaging results, the young group presented greater BOLD signal changes than the OH or OL group. In particular, the young group demonstrated greater BOLD signal changes in middle frontal regions than the OL group in long response time trials. However, the degree of BOLD signal changes was similar between the young and the OH group when processing difficult trials. Even though the neuroimaging results did not show significant difference in terms of brain networks among the three groups, the amount of voxels involved in the task processing may illustrate the differences. When combining the results of brain activations (represented by the amount of voxels) and response time performance, the results showed that the young group recruited the fewest voxels when processing the task and their behavioural performance was the best (i.e. the fastest response time) by viewing Figure 4-26. The OH group involved more voxels than the OL group yet their behavioural performance was similar. When performing difficult trials, the young group recruited the largest amount of voxels, followed by the OH group, and the OL group showed the least amount of voxel involvement.

The young group showed less neural activation than either of the older groups when performing the dot-cross task. The finding is in line with previous studies that showed greater deactivation in young participants than older adults when performing cognitive tasks (Davis et al., 2008; Park et al., 2010). Park and colleagues utilised the categorical/easy and coordinate/difficult spatial processes to observe the differences in default network between young and older adults (Park et al., 2010). The default network is considered to be a set of brain regions which are engaged during a resting state and it encompasses areas from the medial frontal cortex, medial and lateral parietal cortex, and anterior and posterior cingulate and medial temporal areas. Their results showed that young participants exhibited stronger deactivation in the default network than old participants when processing the coordinate/difficult spatial judgment task, possibly related to the specialised and efficient brain activity in young adults. However, such age differences in the default network did not occur in the categorical/easy spatial judgment task. Similarly, Davis and colleagues (2008) demonstrated greater deactivations in posterior medial cortex (e.g. precuneus and lateral PFC) in the young group compared to the older group when undertaking episodic retrieval and visual spatial tasks. Although the current study did not focus on observing differences in deactivation of brain regions or the default network in different age groups, the observation of less neural activity in the young group than the older groups is in agreement with the notion that younger participants utilise brain resources more efficiently when performing cognitive tasks.

When separating the older adults into higher- and lower-performance groups in accordance with their performance on the neuropsychological battery, similar neural networks and behavioural performance were observed in the OH and OL group. Although the OH group seemed to recruit a broader neural network when processing the visuo-spatial memory task (see Figure 4-22), there was no evidence to suggest that the OH group recruited additional brain resources to perform the task. Similarly, there was a trend of greater neural activations in the OH group than the OL group during processing of difficult trials (see Figure 4-24); however, none of the clusters in frontal regions showed significant difference between the two groups. Seven regions were selected to compare BOLD signal changes among the three groups when performing difficult trials. The differences in frontal regions were derived from greater BOLD signal changes in the young than the OL group. However, there was no significant difference between the young vs. the OH group or the OH vs. the OL group. The greater frontal activations during difficult trials in the young group than the older groups may be due to slight experimental manipulation. The response time for young participants was restricted to 2000ms while it was extended to 3000ms for older participants.

A broader (but not significant) neural network observed in the OH group than the OL group indicates that OH participants may have recruited more brain resources to perform the dot-cross task, but they were no better at the task. It is possible that the OH group was defined by performance of the neuropsychological battery. They were better in other aspects of cognitive functions but not the dot-cross task. OH participants may tend to recruit broader/greater neural activations when performing a new/unfamiliar cognitive task. An alternative methodology to observe possible difference in neural activity would be to separate older participants via their specific task performance. This methodological approach may be able to demonstrate different neural networks recruited by older adults who performed better/more poorly on the visuo-spatial task.

Although there was a trend that the OH group showed slightly faster behavioural performance and also more neural activations than the OL group when performing the dot-cross task, the insignificant results restricted possible interpretation. The insignificant findings may be caused by small sample size in the OH group (n=17) and the OL (n=16) group. Statistical power may be too weak to reveal a significant difference between the two groups. The OL group also revealed large variation in response times, which may result in insignificant findings (see Figure 4-21).

It is known that the ageing brain differs from the young brain in various ways. For example, the ageing brain shows reduced white matter integrity (Davis, Kragel, Madden, & Cabeza, 2012; Giorgio et al., 2010; D. J. Madden et al., 2009; Pardo et al., 2007; Park & Reuter-Lorenz, 2009; Voineskos et al., 2012; Zhu, Johnson, Kim, & Gold, 2013) and change in the BOLD signal (D'Esposito, Deouell, & Gazzaley, 2003; Hedden & Gabrieli, 2004; Rajah & D'Esposito, 2005; Reuter-Lorenz & Park, 2010) compared to the young brain. In the current study, an additional analysis adopting age as a covariate suggests that the observed differences between the young and the older groups cannot be attributed to age but to the plasticity of the ageing brain.

In summary, the current experiment observed the underlying neural mechanism in processing categorical and coordinate spatial relations. A similar bilateral neural activation was found in the old and the young group when processing the two visuo-spatial representations. The dominant role of categorical representations was observed throughout the age range. When comparing different brain networks across the young, OH, and OL groups, the young group showed significantly less neural activity than either of the older groups when performing the dot-cross task and their behavioural performance was the best. They also recruited more frontal activity, which is associated with attention and executive functions, when performing difficult trials than the older groups. The significant difference in frontal activity occurred only in the contrast between the young and the OL group. Within older adults, there is a trend that the OH group performed slightly faster on the dot-cross task than the OL group. However, there was no significant difference in the direct comparisons of the whole brain analysis and the analysis associating brain activity with long reaction times (i.e. RT modulation). Significant differences were observed in the young vs. the OL group but not in the contrasts of the OH vs. young group or the OH vs. OL group.

4.4 Summary of Chapter 4

The current chapter contains two experiments. The first experiment included the neuropsychological battery, which examined middle-aged and older adults' general cognitive ability; the second experiment adopted neuroimaging techniques with a developed visuo-spatial STM task, the dot-cross task, in order to observe the underlying neural mechanism. The older participants were further separated into higher- and lower-function groups in order to explore the cognitive and neural differences between the two groups. People with higher- and lower-cognitive ability revealed different cognitive profile in neuropsychological performance (HP vs. LP); The LP group showed more correlations across different cognitive tests than the HP group. In addition, lower-performance participants showed additional association with verbal information when processing the dot-cross task. Hierarchical multiple regression results indicate that the background variables, age and NART scores, can be utilised to predict the performance for the CATCOORD task in the HP group. However, verbal ability was considered to be an index to estimate the performance of the LP group when processing the dot-cross task. In terms of neuroimaging results, the older group showed bilateral neural network during categorical and coordinate processing. When separating the older group into the OH and the OL group, both groups showed similar brain networks when processing the dot-cross task. Both groups exhibited greater neural activations than the young group when processing the dot-cross task. Similar to the young group, the older groups involved frontal activations when performing difficult trials. In particular, the young group demonstrated the greatest neural activity in frontal regions during difficult trials process. Although there was a trend that the OH group revealed greater neural activations than the OL group when performing the visuo-spatial task, cluster-level analysis did not show significant findings in the direct comparison.

The lateralisation effects for categorical and coordinate spatial relations have been well demonstrated in young adults (Bruyer, Scailquin, & Coibion, 1997; Kosslyn et al., 1989; Kosslyn, Maljkovic, Hamilton, Horwitz, & Thompson, 1995; Slotnick & Moo, 2006; van der Ham & Postma, 2010; van der Ham, van Wezel, Oleksiak, & Postma, 2007) as well as patient studies (Kosslyn et al., 1995; Kosslyn, 2006; Palermo et al., 2008). However, the results derived from older people are inconsistent; while some studies suggest that the lateralisation effect was not affected by age (Hoyer & Rybash, 1992; Meadmore et al., 2009), others hold the opposite opinion (Bruyer et al., 1997). The current finding supports the notion that the hemispheric specificity for the two spatial relations is not affected by age. Behavioural lateralisation effects were found in the older group in the current study. Unlike young participants who showed a ceiling effect in accuracy and the lateralisation effects in reaction times in the dot-cross task (see Exp.3), older participants demonstrated the lateralisation effects in accuracy. It may be that older participants found the dot-cross task more difficult to perform than young participants. A trend of the lateralisation effects in the result of reaction times in Experiment 5 (see the result section 4.2.3.1.2) and Experiment 6 (see the result section 4.3.3.1) suggests that the hemispheric effects for categorical and coordinate spatial processes are not influenced by age. As only 200 trials were involved in the dot-cross task for middle-aged and older participants, more practice trials for older adults may result in similar findings to young adults.

Similar neural networks for categorical and coordinate spatial processing were found in older participants as well as young participants. The finding suggests that the two visuo-spatial representations may share a similar neural network. When comparing neuroimaging results between the young and the older groups, the young group demonstrated less neural activity when performing the visuo-spatial memory task and involved more frontal activity when processing difficult trials. Meanwhile, their behavioural performance was better than the older groups. When separating older participants into the OH and OL group, neither neuroimaging nor behavioural results exhibited significant difference between the two groups. The OH group did not recruit additional brain networks when performing the dot-cross task or difficult trials, nor were their response times on the task significantly faster than the OL group.

The current study combined both neuropsychological and neuroimaging results to provide a more complete picture to examine differences between higher- and lower-function adults in healthy ageing. Previous literature examining ageing theory usually utilises a single task approach to compare either OH vs. OL or young vs. older adults. The findings can be biased by the selected task since age-related cognitive decline varies in different cognitive domains (Park et al., 2001b). By including the neuropsychological battery to understand participants' broader cognitive ability and relate their performance to age-sensitive visual spatial memory tasks, the current study was able to examine the scaffolding hypothesis from the integrated results. According to the evidence from both neuropsychological and neuroimaging studies, scaffolding mechanisms were not found in the neuropsychological profile (the HP group) or brain networks (the OH group). However, broader cognitive profile observed in the LP group may exhibit cognitive dedifferentiation. The OH group demonstrated a trend of greater neural activations than the OL group, suggests it may be a marker of being in the OH group rather than the OL group.

Chapter 5. General Discussion

This chapter firstly summarises the main findings of the CATCOORD task (Chapter 2), the dot-cross task (Chapter 3) with young participants, the neuropsychological study with middle-aged and older adults and the neuroimaging study conducted with older adults (Chapter 4). Implications of the primary findings and strengths and limitations of the project are then discussed. Finally, research directions are provided for future work.

5.1 Summary of principle findings

Cognitive ability demonstrates different rates of age-related decline as outlined in the introduction (Chapter 1). For example, spatial ability and psychomotor speed are more affected by age, compared to language ability. Most studies utilise verbal-related tasks to demonstrate compensatory mechanisms in ageing, and evidence from the visuo-spatial domain is lacking. The current project investigates visuo-spatial processing in older adults in order to observe possible cognitive compensation. Categorical and coordinate spatial relations, which have demonstrated hemispheric specificity in the literature, were utilised to investigate compensation mechanisms in ageing. The left hemisphere shows an advantage in processing categorical spatial judgments while the right hemisphere is faster when processing coordinate spatial judgments. The hemispheric characteristics of the two spatial relations could provide evidence of possible scaffolding mechanisms by recruiting additional neural activations in the opposite hemisphere or different brain regions.

Two visuo-spatial short-term memory tasks are utilised in the present project, the CATCOORD task (Chapter 2) and the dot-cross task (Chapter 3). The CATCOORD task presents a set of four stimuli on visual array with categorical or coordinate changes between a reference and a target. Experimental manipulations include encoding times (250ms, 500ms, and 2500ms) (Experiment 1a-1c), retention intervals (500ms, 2000ms, and 5000ms) (Experiment 1a), shifts between reference and target (15mm, 20mm, and 25mm) (Experiment 1a-1c), identity of visual stimuli (unicolour and multiple colours) (Experiment 1c), and auditory verbal interference (spatially relevant words, irrelevant words and colour words) (Experiment 1b and 1c). The manipulations are designed to minimise assistance for categorical spatial relations in order to observe possible boundaries for categorical representations, i.e. where categorical advantage effects may disappear in VSSTM. The results showed better performance on categorical change trials than coordinate change trials, even when the encoding time and retention interval were the shortest, and shift size was the smallest. Moreover, when two of the subcomponents of categorical representations, categorical-verbal and categorical-spatial codes, were interfered with via auditory verbal interference, the categorical advantage effect was still observed. These findings support the notion that categorical spatial representations are an intrinsic property in VSSTM. The neuroimaging results with the CATCOORD task (Experiment 2) revealed bilateral activations when processing both categorical and coordinate change trials. This suggests that underpinning neural networks for the two visuo-spatial processes may be similar. However, hemispheric lateralisation for the two types of visuo-spatial processing was not found when stimuli were presented to the whole visual field. The lack of hemispheric lateralisation effects for the two visuo-spatial representations in the CATCOORD task restricts the possibilities for exploring cognitive scaffolding in ageing. Therefore, another visuo-spatial STM task was adopted in the next experiment.

A half visual field task, the dot-cross task, was utilised to explore hemispheric lateralisation effects for categorical and coordinate spatial relations (Experiment 3). Although previous literature has demonstrated an advantage of the left hemisphere when processing categorical spatial judgments and an advantage of the right hemisphere in processing coordinate spatial judgments with the original version of the dot-cross task, the modified version in the present project applied more strict manipulations to examine the hemispheric effects. Specifically, a spatial judgment cue is not provided after an encoding image is presented, which requires participants to encode all visuospatial information during the encoding stage. Visual cues are replaced by auditory non-verbal cues in order to minimise intrusion from verbal codes. The results showed hemispheric lateralisation effects with the modified dot-cross task. Participants responded faster for categorical spatial judgments when stimuli were presented on the right visual field/left hemisphere; they were also faster in responding to coordinate judgments when stimuli were presented on the left visual field/right hemisphere. In addition, the advantage of the left hemisphere in processing categorical spatial relations always occurs whereas the right hemisphere advantage for coordinate spatial relations requires time to develop. The neuroimaging results (Experiment

4) demonstrated bilateral activations when processing categorical or coordinate spatial judgments. Importantly, participants showed more frontal activations when processing more difficult coordinate judgment trials than they did for categorical judgment trials. Since frontal regions are associated with attention and executive functions, another possible cognitive compensation mechanism could be formed by recruiting more resources from attention and executive functions. As hemispheric lateralisation effects have been observed with the modified dot-cross task as well as a possible form of cognitive scaffolding, the following experiment utilised it and also included neuropsychological tests.

Experiment 5 recruited 20 middle-aged (aged between 45 and 59 years old) and 51 older adults (aged above 60) to perform a series of neuropsychological tests to investigate general cognitive performance, including psychomotor speed, attention/executive functions, verbal ability, and spatial ability. The CATCOORD task and the dot-cross task were also included to explore visuo-spatial processing. It was noted that most of the oldest old adults were categorised to a lower performance group. Therefore, middle-aged and older adults who were aged below 70 years old were re-divided into the higher- and lower-cognitive performance (HP and LP) group in order to explore cognitive profile in the higher performance group. The HP group showed less association across different cognitive tasks compared to the LP group. An exploratory analysis utilised PCA, which extracted three principle components among the neuropsychological tests; an attention-executive component, a verbal component and a STM component. Pearson correlation was performed to investigate the relationship between the two visuo-spatial STM tasks and the principle components. The results showed a positive association between the verbal component and the dot-cross task in the LP group. Hierarchical regression suggests that the verbal component explained a significant amount of variance when performing the dot-cross task in the LP group.

Middle-aged participants were recruited as a reference group for the two visuo-spatial STM tasks; hence they were not included in the neuroimaging study. Thirty-eight older participants (age range from 60 to 86 years old) from Experiment 5 were recruited to perform the dot-cross task in the scanner (Experiment 6). Similar to the findings with young participants (Experiment 4), bilateral activations were observed when processing categorical or coordinate judgments. Categorical spatial judgments required greater activation than coordinate judgments, especially in the posterior parietal-temporal region and middle-frontal region. Older participants who participated in the fMRI study were further divided into the old-higher (OH) and old-lower (OL) performance group in order to compare their neural activities with the young group. The behavioural results showed that while accuracy of performance remained similar among the three groups when performing the dot-cross task, the young group showed the fastest reaction times. There was no significant difference in reaction times between the OH and OL group. The neuroimaging results showed that the young group had the fewest brain regions activated when processing the task and the greatest BOLD signal changes in frontal regions when processing difficult trials. Within the old groups, the OH group showed broader neural activations than the OL group globally but the difference was not significant at cluster-level analysis. The OH group demonstrated a trend of greater BOLD signal changes than the OL group in different brain regions but none of the clusters reached a significant level in cluster-level analysis except the left parahippocampal gyrus. The significant difference in BOLD signal changes when performing difficult trials was derived from the contrast between the young and OL group but not the OH and OL group. Overall, the young group showed the fewest brain activations when performing the dot-cross task and their behavioural performance was the best (i.e. the fastest response times) among the three groups. Moreover, the BOLD signal changes during processing difficult trials were the greatest in the young group. The difference between the OH and the OL group was not significant in behavioural or neuroimaging results.

5.2 Implications of the primary findings

5.2.1 Categorical and coordinate spatial representations in VSSTM

5.2.1.1 The CATCOORD task

The CATCOORD task was designed to investigate whether difference in categorical and coordinate spatial representations can be observed in a whole visual-field task. Dent (2009) utilised a similar experimental paradigm to demonstrate a consistent categorical advantage effect in VSSTM. The current experimental manipulations explored a possible categorical threshold by minimising categorical information in visuo-spatial representations. The findings showed that with a short encoding time (e.g. 250ms), a short maintenance interval (e.g. 500ms), and a subtle distance change between a reference and a target (e.g. 15mm), the performance on categorical change trials was still better than coordinate change trials.

There are some experimental issues to be discussed. For instance, encoding times (250ms, 500ms, and 2500ms) were designed as a between-subject variable in Experiment 1a, while maintenance intervals (500ms, 2000ms, and 5000ms) and shift sizes between target and reference (15mm, 20mm, and 25mm) were designed as within-subject variables. The fact that results did not show a significant effect of encoding time in the CATCOORD task might be due to the between-subject design. Manipulation of shift size demonstrated a main effect in the CATCOORD task. However, better categorical performance was still found in the smallest shift compared to the greater shifts in coordinate trials. It is possible that a 15mm shift between a reference and a target on a visual array may still be located within the categorical boundary and lead to a categorical advantage effect in VSSTM. However, there is no literature investigating detection threshold for spatial changes to date. Future studies could utilise shift sizes that are smaller than 15mm to explore a possible categorical boundary.

Auditory verbal interference was adopted in Experiment 1b and 1c in order to interrupt verbal labels for categorical spatial representations. The effect of auditory verbal interference was difficult to interpret in the current project. Spatially relevant words seemed to trigger participants to adopt a visuo-spatial related memory strategy as faster responses for both spatial changes were observed in Experiment 1b. In Experiment 1c, where two sub codes of categorical representations, categorical-verbal and categorical-perceptual codes, were interfered with via spatially relevant and colour words, the categorical advantage effect was still found. Auditory verbal intervention did not affect categorical or coordinate performance. It is possible that the verbal interference for categorical-perceptual codes (i.e. playing colour words) may still intrude on categorical-verbal codes given the nature of the design. Alternatively, the auditory verbal intervention adopted in the experiment may be too weak to interfere with categorical representations. Another possibility for the observed categorical advantage effect may be due to the design of the verbal interference. In Experiment 1b and Experiment 1c, participants repetitively heard four pre-recorded interference words in the same order. This methodology may lead to participants habituating and to the development of a memory strategy, such as ignoring the interference words; hence the impact of the interference words was minimised. To play interference words less predictably may draw participants' attention to the interference words throughout visuo-spatial processing and maximise the effect of interference on categorical spatial representations. Type of interference, e.g. categorical-verbal or categorical-spatial interference, could be designed as a within-condition variable so that the interference words could not be predicted. Moreover, increasing the number of interference words could also decrease expectancy during the experiment procedure and achieve the purpose of interruption. In addition to playing interference words, articulatory suppression is another type of interference methodology. For instance, Dent utilised articulatory suppression to interfere with categorical spatial representations in VSSTM but the categorical advantage effect was still observed (Dent, 2009). Kessels and Postma utilised articulatory suppression with an object-relocation task and found inconsistent effects of verbal interference. Specifically, performance of object-location binding memory (e.g. reconstruction of the objects to positions with spatial clues) and combined memory of objects and locations (e.g. reconstruction of the objects to positions without spatial clues) were impaired but not position only memory (e.g. reconstruction of the positions for the objects) (Kessels & Postma, 2002). These inconsistent findings on verbal interference require more research to investigate its effect on VSSTM. Postma & DeHaan (1996) examined articulatory suppression effects on different memory loads (e.g. a set of 7 or 10 to-be-remember items in a visual array). The results indicated that articulatory suppression affects memory performance for larger array size. The visual-spatial array of the CATCOORD task may be too small to reveal the effects of verbal interference, as it presents four items only. Future studies could increase the number of to-be-remembered objects with the CATCOORD task in order to explore the effects of verbal interference in VSSTM.

Experiment 2 was the first neuroimaging study that investigated neural activity during categorical and coordinate spatial processing with the CATCOORD task. The results showed bilateral activation when processing categorical or coordinate change trials when stimuli were presented to the whole visual field. Interestingly, the coordinate spatial judgments showed similar behavioural performance (i.e. accuracy and reaction times) to categorical spatial judgments in the scanner. The categorical advantage effect, which was consistently found in Experiment 1a to Experiment 1c, was not observed in the scanner. It is possible that the experimental environment within MR scanner, e.g. darker space and restricted head movements, led to an artefact which benefited coordinate spatial representations. Hemispheric lateralisation effects for the two spatial processes were not found in Experiment 2. Previous studies have demonstrated that the right hemisphere advantage for coordinate spatial processing occurs in short time courses (van der Ham et al., 2009, 2007). As a result, fMRI is not an optimal neuroscience technique to demonstrate lateralisation effects due to its lack of temporal resolution. Studies utilising event-related potential (ERP), which is a time-sensitive neuroscience technique, with a dot-cross task have shown a clear right hemispheric advantage for coordinate trials during the encoding stage but not the left hemisphere advantage for categorical trials (van der Ham et al., 2010; van der Lubbe et al., 2006).The findings suggest that the right hemisphere advantage for coordinate processing exists in an early stage of VSSTM, within 300-500ms after the first stimulus is presented. Future studies intending to investigate hemispheric lateralisation effects with the CATCOORD task could adopt such technique.

5.2.1.2 The dot-cross task

The modified version of the dot-cross task utilised stricter methodology to examine hemispheric lateralisation effects for categorical and coordinate spatial processing, by delaying presentation of cues for spatial judgments and replacing visual-verbal cues with non-verbal auditory tones (Experiment 3). Participants showed faster responses for categorical judgments when stimuli were presented on the left hemisphere and they were faster in processing coordinate judgements if stimuli were presented on the right hemisphere. Importantly, exploratory analysis showed that the left hemisphere advantage in processing categorical judgments persisted in VSSTM, whereas the right hemisphere advantage in processing coordinate judgments required time to develop. Unlike the previous study which suggested that the right hemisphere advantage for coordinate processing is sensitive to short time courses (van der Ham et al., 2007), the modified dot-cross task demonstrates that longer practice time/more practice trials are required to reveal the right hemisphere advantage for coordinate spatial processing. The findings indicate that, firstly, the modified version of the dot-cross task is suitable for examining lateralisation hemispheric effects for the two visuo-spatial representations. Secondly, reaction time is a better index than accuracy to reveal hemispheric advantages for the spatial processes (Kosslyn et al., 1989).

The neuroimaging results of the dot-cross task (Experiment 4) did not show hemispheric lateralisation effects for categorical and coordinate spatial processing, unlike the previous study (van der Ham et al., 2009). This may be due to several changes to the experiment paradigm. First of all, the visual-verbal cues from the original paradigm were replaced with non-verbal auditory cues and the presentation of the cues was delayed to after the encoding stage. These manipulations minimized verbal intrusion and prevented participants from predicting types of judgment at the beginning of a trial. Secondly, participants experienced fewer trials (176 trials) than van der Ham's study (420 trials) in the scanner. As Experiment 3 demonstrated, the hemispheric effects require practice/more time to develop. Although the analysed behavioural data were from the later part of the task and were collected inside the scanner, changes to the experimental environment (a behavioural experiment room vs. MR scanner) may reduce or eliminate practice effects. The number of trials performed in the scanner may therefore have been insufficient to reveal the hemispheric effects. Thirdly, the experimental design was an event-related design instead of a block design. Types of spatial judgments were unpredictable in the modified dot-cross task, hence the lateralisation effects may have been weakened. Finally, the neuroimaging results did not apply analysis with regression coefficient to illustrate lateralisation effects, yet a difference between the two visuo-spatial processes was still found. Specifically, activation in frontal regions was found when processing more difficult coordinate change trials (i.e. judgments that required longer reaction times) but not categorical change trials.

Bilateral neural activation was found in different paradigms (the CATCOORD task and the dot-cross task), which indicates that the two spatial representations may rely on similar neural networks. The modified dot-cross task adopted a stricter method to examine hemispheric processing for categorical and coordinate spatial relations. The findings suggest that the two spatial representations share similar networks, and that coordinate spatial relations are considered to be more difficult judgments hence require the resources of attention and executive functions. Hemispheric lateralisation effects demonstrated in van der Ham's study might be due to participants changing their approach to the task when knowing the type of spatial judgment in advance.

5.2.2 The ageing study

Experiment 5 consisted of a battery of neuropsychological tests and the two visuo-spatial STM tasks with middle-aged and older adults. The CATCOORD task showed similar results for the middle-aged and older groups and the young group. The categorical advantage effect was consistently found across different age groups, suggesting that the dominant role of categorical spatial representations in visuo-spatial capacity exists across the lifespan. Larger shift size leads to better memory performance in all age groups. More importantly, the sensitivity of coordinate spatial relations to shift sizes was observed in the middle-aged and older groups as well as the young. The age difference only existed in categorical change trials. In particular, middle-aged participants were more accurate on judging categorical change trials than older participants. The age difference did not appear in coordinate change trials. It is possible that coordinate spatial relations require precise visual-spatial information and a lot of practice in order to detect the changes and so age becomes a less important variable for coordinate spatial relations.

The modified dot-cross task demonstrated hemispheric lateralisation effects in accuracy in the older group but not in the middle-aged group. The missing lateralisation effect in the middle-aged group may be due to a small sample size (n=20). Small sample size accompanied by larger variation (see Figure 4-13) is likely to result in non-significant findings. On the other hand, the lateralisation effect was shown in the older group; categorical change trials were responded to more accurately if the stimuli were presented on the left hemisphere whereas coordinate change trials were performed better if the stimuli were presented on the right hemisphere. Moreover, the RT result showed a hint of the lateralisation effect by demonstrating more rapid responses for categorical spatial judgments when the stimuli were presented on the left hemisphere. Older participants also demonstrated a trend of longer reaction times than the middle-aged group, which is consistent with previous work with a dot and bar task (Meadmore et al., 2009). The finding that the older group revealed the lateralisation effect for the dot-cross task only in accuracy could be attributed to the difficulty of the visuo-spatial memory task. Older participants found the task difficult enough that the lateralisation effect was revealed in accuracy, whereas the young participants demonstrated the lateralisation effect in the variation of reaction time. Another possibility which may explain the weakened/absent lateralisation effects in the middle-aged and older group may be the reduced amount of trials in the dot-cross task. The trial number was reduced from 340 trials (for the young group) to 200 trials (for the middle-aged and older group) to enable the participants to perform other neuropsychological tests. More trials in the dot-cross task may lead to the lateralisation effect reaching a significant level.

Older adults showed more interconnections among cognitive tasks than middle-aged adults, indicating that older participants utilised various cognitive abilities when performing cognitive tasks. However, age was particularly associated with performance on psychomotor and spatial ability tests, but not attention and executive functions or verbal ability. Age is suspected not to affect all neuropsychological performance. When separating older participants into the OH and OL groups, the OL group contained a higher proportion (48%) of people who were aged above 70 years old than the OH group (16%). The finding of more correlations across different cognitive tasks in the OL group may be driven by these oldest-old participants. In order to explore possible scaffolding mechanisms, middle-aged and older adults (excluding those aged above 70 years old) were mixed and split into the higher-performance (HP) and lower-performance (LP) group. Similar to the OL group, a broad cognitive profile was found in the LP group. The result may be caused by inefficient application of cognitive strategies (e.g. failure to utilise scaffolding mechanisms) or failure to filter irrelevant resources and to select helpful cognitive resources when performing the tasks. It is also possible that the cognitive profile with more interconnectedness across different cognitive tasks in the LP group represents a phenomenon of dedifferentiation in ageing (see the notion in Chapter 1). Although the correlation analysis could not provide a causal relationship, it is speculated that LP participants lacked the ability to select relevant cognitive resources, resulting in poor performance on the cognitive tasks. Gallagher and colleagues utilised a battery of neuropsychological tests to investigate differences in cognitive profile between bipolar disorder patients when depressed and healthy control participants (Gallagher, Gray, Watson, et al., 2014). The results showed more correlations across different neuropsychological tests in bipolar depression patients, compared with controls. The more interconnectedness across different cognitive tasks observed in LP participants and bipolar depression patients may be caused when cognitive resources are low or diminished, but not specific to ageing per se.

Exploratory analysis of the neuropsychological battery study included PCA to attribute cognitive tasks to specific cognitive domains and to investigate the relationship between the principal components and the two visuo-spatial memory tasks. The performance of the dot-cross task was correlated with the verbal component in the LP group. LP participants may have recruited additional verbal information to ‘scaffold’ the performance, yet such a strategy was unsuccessful, as it did not assist them to perform better than the HP group on the task. Alternatively, it may represent a dedifferentiation process in cognitive decline since the LP group did not perform significantly worse on the behavioural results (RTs) than the HP group. The analysis of hierarchical regression also suggested that the verbal component could explain the task performance in the LP group. However, the association between verbal ability and spatial memory performance was found in the dot-cross task, but not the CATCOORD task, which suggests that the observed results may be task dependent. Other visuo-spatial tasks that examine other types of spatial ability could be applied to clarify whether the observed correlation was a coincidence.

The neuroimaging results showed bilateral activations in the young and the old group (Experiment 4 and Experiment 6), suggesting that categorical and coordinate spatial processing may share a similar neural network. The underlying neural mechanisms for visuo-spatial processing were not affected by age. Older participants were divided into old-higher (OH) and old-lower (OL) group according to their performance on the neuropsychological battery and to further compare neural networks with the young group. There was significant difference in terms of behavioural performance (RTs for the dot-cross task) and neural networks between the young and the older groups. However, there was no significant difference within older groups, i.e. the OH vs. OL group. It is worth mentioning that the results showed a trend of better behavioural performance (e.g. faster reaction times) and greater neural activations in the OH than the OL group. When comparing brain activities during processing of difficult trials, frontal regions showed greater BOLD signal changes than other brain areas in all groups. Moreover, the young group showed significantly greater

BOLD signal changes than the OL group when performing difficult trials. However, the OH group did not show significantly greater BOLD signal changes than the OL group. Performance of the OH group seemed to be placed in between the young and the OL group and the results of the young vs. OH and the OH vs. OL group were not significantly different. Although the OH group presented possible scaffolding mechanisms by showing globally greater neural activations and a trend of faster responses than the OL group when performing the dot-cross task, none of the results was significant. The lack of significant difference between the OH and the OL group could be due to small sample size and larger variations among older adults. Possible differences between the OH and OL group may be revealed by a larger sample size. Another possible explanation for the insignificant findings between the OH and the OL group is that 'scaffolding' mechanisms did not occur in healthy ageing. The broader neural networks observed in older adults compared to the young was caused by the 'dedifferentiation' processing in ageing. Whether the broader neural network in older adults is a compensatory mechanism or a dedifferentiation process requires further examination.

Previous studies have demonstrated different patterns associated with better performance in the elderly, such as recruiting extra brain regions or utilising different cognitive resources when performing a cognitive task. For example, Cabeza and colleagues showed that older adults with better performance on a source memory task exhibited bilateral activation, whereas those with poorer task performance exhibited unilateral activation, similar to the pattern in young participants (Cabeza et al., 2002). Gallagher and colleagues demonstrated another form of cognitive scaffolding showing that patients utilised additional verbal information when performing a visuo-spatial memory task (Gallagher, Gray, & Kessels, 2014). The current project observed young participants showing more activation in frontal regions, which are associated with attention and executive processing, than other brain regions when performing difficult coordinate trials. The OH group also showed globally greater BOLD signal changes than the OL group when performing difficult trials in the dot-cross task. The findings indicate different scaffolding mechanisms i.e. recruitment of more attention and executive resources during a visuo-spatial processing task. This finding is in line with the notion of posterior-anterior shift in ageing (PASA) (see Chapter 1). Future studies should include a larger sample size in order to examine this hypothesis. It is likely that cognitive scaffolding is a dynamic process (as proposed by the scaffolding theory of ageing and cognition (STAC) (see Chapter 1)), and it is not restricted to a specific form of compensatory mechanisms in ageing.

5.3 Strengths and limitations of the current project

The present project utilised visuo-spatial related tasks to explore possible scaffolding mechanisms in ageing, while most studies examine this issue by utilising verbal related tasks (Cabeza et al., 2002; Mattay et al., 2006; Persson et al., 2006). The two visuo-spatial short-term memory tasks, the CATCOORD task and the dot-cross task, were carried out in young, middle-aged and older adults. By involving different age groups it is possible to observe categorical and coordinate spatial processing across the lifespan. The similar findings of the CATCOORD task among different age groups suggest that categorical spatial relations are the dominant visuo-spatial representations in VSSTM. Importantly, hemispheric lateralisation effects observed in young and older adults in the dot-cross task indicate that the hemispheric specificity for categorical and coordinate spatial processing is not affected by age.

The current project adopted a battery of neuropsychological tests to observe broader cognitive ability in older adults and to further investigate different cognitive profiles between older adults with better and poorer cognitive performance when performing unfamiliar visuo-spatial STM tasks. This is thought to be a better method to examine cognitive scaffolding; a possible approach by which different cognitive domains could be utilised to maintain cognitive performance in older adults. For instance, older participants with better cognitive performance may adopt additional attention resources and/or verbal information in order to assist visuo-spatial performance. The neuropsychological battery consisting of various cognitive domains was able to explore these possibilities. The neuroimaging study with older adults (Experiment 6) provided supplementary evidence of scaffolding mechanisms in the ageing brain. By combining neuropsychological profile and neuroimaging results, the project is able to provide a better understanding of scaffolding mechanisms in ageing.

There are some methodological issues which should be discussed. For instance, the middle-aged and the older group showed similar cognitive performance in the neuropsychological battery which may be due to sample selection. Older participants were recruited via different sports clubs (e.g. tennis club, cycling club), IoN volunteer newsletter, Newcastle Elders Council, and age UK, and their cognitive ability may be less affected by age than those who have minimal social interactions. Factors such as life style, e.g. exercise, or characteristic/personality, e.g. willingness to take on challenges, have been shown to be associated with preserved cognitive ability in ageing (Deary et al., 2009; Hedden & Gabrieli, 2004; Kramer, Erickson, & Colcombe, 2006; Myint & Welch, 2012). The current project recruited only healthy participants. The findings of the cognitive profile with more correlations across different cognitive tasks in the LP group or globally greater neural activity in the OH group are only relevant to the healthy ageing process. A median split was performed on the recruited participants. There was no evidence that the members of the lower performance group represented those with truly poorer cognitive ability in the older population. It is possible that the LP group in the current project was still from the population with good cognitive ability. Moreover, a small sample size in the ageing study leads to the experiment's lack of statistical power.

The current project is a cross-sectional study that observed visuo-spatial processing in different age groups and inferred that the difference between the three groups relates to the process of "ageing". A drawback of this type of methodology is that individual differences are underestimated or ignored. For example, the OH group showed greater neural activity than the OL group when processing the dot-cross task or the difficult trials, which is suggested as a form of cognitive scaffolding. However, other possibilities, such as OH participants having applied this pattern of neural activity since their early years, should also be considered. A longitudinal methodology would provide a comprehensive view of changes in cognitive abilities over time and explore possible applications of cognitive scaffolding in old age.

A stricter experimental paradigm was utilised in the current project than the original version (van der Ham et al., 2009, 2007) to examine categorical and coordinate spatial relations. The modified version of the dot-cross task minimises possible verbal information and forces participants to rely on visuo-spatial representations when performing the task. The manipulation may reduce the degree of cognitive scaffolding with other cognitive resources. Cognitive scaffolding may emerge when the paradigm is less strict, e.g. when types of spatial judgments are predictable and/or verbal information assistance is available during visuo-spatial processing.

5.4 Research directions for future work

The current project has identified important and interesting findings on visuo-spatial processing across lifespan and differences in cognitive profiles between good and poor performance older adults. Some of these findings could be explored in future research and lead to better understanding of these cognitive processes.

The CATCOORD task has been explored in great detail in the current project. However, other experimental manipulations could be applied to further investigate categorical and coordinate spatial representations in VSSTM. For example, different durations of encoding times were set as a between-subject variable in Experiment 1a; researchers who wish to explore the effects of categorical and coordinate spatial relations at an early stage of visuo-spatial processing could set different encoding times as a within-subject variable. The categorical advantage effect was found in the smallest shift size (15mm) in the CATCOORD task. The 15mm shift may still be within categorical boundary resulting in better detection for categorical changes. Smaller shift sizes could be adopted in future to explore a possible categorical boundary, which may eliminate the categorical advantage in VSSTM.

Auditory verbal intervention did not affect categorical or coordinate performance in the CATCOORD task. It is possible that the auditory verbal intervention adopted in the current project was too weak to interfere with categorical representations. Future studies intending to enhance the effects of interference on the two spatial representations could adopt spatial tapping with attributes that belong to the spatial relations. For instance, spatial tapping that requires participants to tap on broad/abstract spatial relations, e.g. different quadrants, may interfere with categorical spatial representations only. On the other hand, spatial tapping which includes precise spatial relations may influence coordinate spatial processing (van der Ham & Borst, 2011).

The design of Experiment 1a to Experiment 1c focused manipulations on minimising categorical information in visuo-spatial representations, including minimising encoding times, retention times, shift sizes, and introducing verbal interferences in the CATCOORD task. The categorical advantage effect has been consistently observed in these experiments, which suggests that categorical spatial representations are a primary process in VSSTM (Dent, 2009). Future studies attempting to examine the distinct spatial representations of categorical and coordinate relations could apply a different approach by enhancing characteristics of coordinate spatial representations. For instance, specific distance judgments (e.g. requiring participants to judge specific distance changes; 15mm, 20mm, or 25mm) could be included in the CATCOORD task.

The CATCOORD task did not provide spatial judgment cues prior to each trial and it presented visuo-spatial stimuli at the centre of the screen. This paradigm design was unable to examine hemispheric lateralisation effects for categorical and coordinate spatial relations. Future studies aiming to investigate hemispheric specificity with the CATCOORD task could amend the experiment procedure, by providing instruction on spatial judgments prior to a memory trial or by presenting the visual array to a half visual field. The former methodology examines whether the lateralisation effect derives from specific memory strategy for categorical and coordinate spatial processing whereas the latter methodology examines whether the lateralisation effect occurs when types of spatial judgments are not provided and the number of to-be-remembered items is increased.

The missing categorical advantage effect in the CATCOORD task in an MR scanner may be due to an artefact, such as greater illumination contrast between the tunnel and the screen causing visual residual afterimages. Restricted head movements may also enhance detection of subtle distance changes, i.e. coordinate spatial relations. Future study could adopt experiment equipment that fixed participants' chin/head and a darker experiment room to resemble the environment in an MR scanner. Researchers could then investigate effects of visual traces and whether the disappearing categorical advantage effect in an MR scanner is coincidence.

The modified version of the dot-cross task demonstrated the lateralisation effect in the behavioural experiment (Experiment 3). However, the task did not show hemispheric specificity in the neuroimaging results (Experiment 4). As highlighted in section 5.2.1.2, there are several different manipulations between the original version (van der Ham et al., 2009) and the modified version. Future work could increase the number of trials performed inside the scanner or provide spatial judgment cues prior to a trial to observe hemispheric lateralisation effects for the two spatial representations. Coordinate spatial representation is thought to be sensitive to short time courses (van der Ham et al., 2009, 2007), yet one of the drawbacks of the fMRI technique is lack of time sensitivity. Future studies could apply ERP, which is sensitive to time resolution, along with fMRI to investigate neural activity during visuo-spatial processing.

The current project did not observe cognitive scaffolding in the neuropsychological battery study in healthy population. The HP group did not utilise verbal or attention/executive ability to perform the visuo-spatial memory tasks. Rather, the LP group showed stronger verbal association when performing the dot-cross task. This finding is different from a previous patient study (Gallagher, Gray, & Kessels, 2014), which suggested verbal scaffolding in bipolar depressed patients when performing a visuospatial task. Different populations could be included in future to explore scaffolding mechanisms for age-related cognitive decline and pathological cognitive decline. In addition, only the dot-cross task showed significant association with verbal ability in the LP group. Different types of visuo-spatial tasks could be adopted in future to clarify the relationship between verbal ability and visuo-spatial processing.

The lack of significant difference between the OH and OL group may be due to a small sample size in the current project. There was no evidence to indicate that the members of the HP group or the LP group were representative of those with truly good or poor cognitive ability in the older population. Future studies could include a larger sample size in order to obtain distinct differences between high- and low-cognitive performance groups.

Finally, future work intending to observe age-related cognitive decline and scaffolding mechanisms could adopt a longitudinal approach. While the present cross-sectional study attempts to explain possible scaffolding mechanisms via different cognitive profiles from different performance groups, a longitudinal study could provide a complete individual cognitive profile across lifespan. This approach may be more appropriate to investigate scaffolding mechanisms developed in response to age-related cognitive decline.

In conclusion, the current project demonstrated a robust categorical advantage effect in a series of experiments with the CATCOORD task. The findings support the notion that categorical representations are an intrinsic property in VSSTM. Hemispheric lateralisation effects for the two spatial representations (behaviourally) occurred only when the stimuli was presented on a half visual field. That is, both hemispheres could process categorical and coordinate spatial representations, albeit with varying processing speed depending on the hemisphere. Hemispheric specificity for the two spatial processes was not affected by age; hemispheric lateralisation effects were found in older adults as well as the young. A pattern of dedifferentiation was observed in the lower cognitive performance group, as they exhibited more interconnectedness across different cognitive tasks than the higher performance group. Neuroimaging results suggest that the underlying neural mechanisms for categorical and coordinate spatial processing may be similar across lifespan. Bilateral activations were found in both the young and the older groups during categorical and coordinate processing. Young participants demonstrated a form of compensatory mechanisms by recruiting attention and executive resources when performing difficult coordinate trials. When comparing neuroimaging results between young and older participants, young participants demonstrated less neural activity than older participants. However, there was no significant difference between the OH and OL groups. The young group also showed greater BOLD signal changes in frontal regions than the older groups. Again, the difference between the OH and OL group was not significant. Nevertheless, it is worth mentioning that a hint of greater frontal activation was found in the OH group than the OL group when performing difficult trials, which may be the presence of a scaffolding mechanism. Future research following recommendations provided in this chapter could enrich our knowledge of categorical and coordinate spatial processing in VSSTM and lead to a better understanding of cognitive scaffolding mechanisms when confronting age-related cognitive decline.

Experiment 1a:CATCOORD task with unicolour, without interference

Analysis 1: 3-way ANOVA

Spatial relations (CAT and COORD) vs. Retention intervals (500ms, 2000ms, and 5000ms) vs. Encoding times* (250ms, 500ms, and 2500ms)

Accuracy	*df*	*F*	*P*	Post-hoc		*t*	*p*
Retention × Encoding	(4,66)	0.62	0.649				
3 way interaction	(8,132)	2.70	*0.009*	Retention COR_2000ms	Encoding 250ms vs. 500ms	2.81	0.010
RTs							
Retention × Encoding	(4,66)	0.57	0.688				
3 way interaction	(8,132)	0.68	0.709				

Analysis 2: 4-way ANOVA

Spatial relations (CAT and COORD) vs. Shift sizes (15mm, 20mm, and 25mm) vs. Retention intervals (500ms, 2000ms, and 5000ms) vs. Encoding times* (250ms, 500ms, and 2500ms)

Accuracy	*df*	*F*	*P*	Post_hoc	*t*	*p*
Shift × Encoding	(4,66)	0.34	0.849			
Retention × Encoding	(4,66)	1.59	0.187			
Retention × Shift	(4,132)	0.65	0.629			
Spatial relations × Retention × Encoding	(4.66)	0.20	0.936			
Spatial relations × Shift × Encoding	(4,66)	1.01	0.410			

Accuracy (Cont.)	*df*	*F*	*P*	Post_hoc		*t*	*p*
Spatial relations × Retention × shift	(4,132)	0.32	0.864				
Retention × Shift × Encoding	(8,132)	0.72	0.671				
4 way interaction	(8,132)	0.86	0.555				
RT							
Shift × Encoding	(4,66)	3.05	*0.023*	Encode 250ms	Shift 15mm vs. 20mm	6.17	<0.001
					Shift 20mm vs. 25mm	2.26	0.045
					Shift 15mm vs. 25mm	6.38	<0.001
				Encode 500ms	Shift 15mm vs. 20mm	3.00	0.012
					Shift 20mm vs. 25mm	3.06	0.011
				Encode 2500ms	Shift 15mm vs. 20mm	4.10	<0.001
					Shift 20mm vs. 25mm	2.91	0.014
					Shift 15mm vs. 25mm	5.67	<0.001
Retention × Encoding	(4,66)	0.83	0.513				
Retention × Shift	(4,132)	3.36	*0.012*				
Spatial relations × Retention × Encoding	(4,66)	0.18	0.947				
Spatial relations × Shift × Encoding	(4,66)	3.29	*0.016*	Encode 2500ms	Shift 15mm CAT vs. COORD	-3.17	0.009
Spatial relations × Retention × shift	(4,132)	0.46	0.765				
Retention × Shift × Encoding	(8,132)	0.74	0.655				
4 way interaction	(8,132)	0.70	0.688				

N.B. * indicates that the variable (Encoding times) is a between-subject variable.

Experiment 1b: CATCOORD task with unicolour, with/without auditory verbal interference

Analysis 1: 3-way ANOVA

Spatial relations (CAT and COORD) vs. Encoding times (250ms, 500ms, and 2500ms) vs. interference types* (Spatial interference, Irrelevant interference, and Silent)

Accuracy	*df*	*F*	*P*	Post-hoc		*t*	*p*
Encoding × Interference	(4,66)	0.81	0.521				
3 way interaction	(8,132)	0.01	0.902				
RT							
Encoding × Interference	(4,66)	2.633	*0.042*	Spatial interference	Encoding 500ms vs. 2500ms	-4.82	0.001
					Encoding 250ms vs. 2500ms	-2.47	0.031
				Irrelevant interference	Encoding 500ms vs. 2500ms	-2.50	0.029
				Silent	Encoding 500ms vs. 2500ms	-3.65	0.004
					Encoding 250ms vs. 2500ms	-4.73	0.001
3 way interaction	(8,132)	1.67	0.110				

Analysis 2: 4-way ANOVA

Spatial relations (CAT and COORD) vs. Encoding times (250ms, 500ms, and 2500ms) vs. shift sizes (15mm, 20mm, and 25mm) vs. interference types* (Spatial interference, Irrelevant interference, and Silent)

Accuracy	*df*	*F*	*P*	Post-hoc	*t*	*p*
Shift × Interference	(4,66)	0.84	0.504			
Encoding × Interference	(4,66)	0.75	0.561			
Encoding × Shift	(4,132)	1.45	0.221			
Spatial relations × Encoding × Interference	(4,66)	1.46	0.224			
Spatial relations × Shift × Interference	(4,66)	0.74	0.566			

Accuracy (Cont.)	*df*	*F*	*P*	Post-hoc		*t*	*p*
Spatial relations × Encoding × Shift	(4,132)	1.405	0.236				
Encoding times × Shift × Interference	(8,132)	0.44	0.898				
4 way interaction	(8,132)	0.27	0.975				
RT							
Shift × Interference	(4,66)	3.19	*0.019*	Silent	Shift 20mm vs. 25mm	2.37	0.037
					Shift 15mm vs. 25mm	2.66	0.022
Encoding × Interference	(4,66)	2.86	*0.030*	Spatial interference	Encoding 500ms vs. 2500ms	-4.56	0.001
					Encoding 250ms vs. 500ms	-2.28	0.044
				Silent	Encoding 500ms vs. 2500ms	-3.20	0.008
					Encoding 250ms vs. 500ms	-4.42	0.001
Encoding × Shift	(4,132)	0.76	0.552				
Spatial relations × Encoding × Interference	(4,66)	1.12	0.357				
Spatial relations × Encoding × Shift	(4,66)	0.74	0.570				
Spatial relations × Shift × Interference	(4,132)	0.15	0.961				
Encoding times × Shift × Interference	(8,132)	0.36	0.939				
4 way interaction	(8,132)	1.60	0.132				

N.B. * indicates that the variable (Interference types) is a between-subject variable.

Experiment 1c: multiple colour, with/without auditory verbal interference

Analysis 1: 3-way ANOVA

Spatial relations (CAT and COORD) vs. Encoding times (250ms, 500ms, and 2500ms) vs. Interference types* (Spatial interference, Irrelevant interference, Colour interference, and Silent)

Accuracy	*df*	*F*	*P*	Post-hoc		*t*	*p*
Encoding × Interference	(6,88)	0.89	0.509				
3 way interaction	(18,264)	1.844	*0.017*	Spatial interference	Encoding 500 CAT vs. COORD	4.67	0.001
					Encoding 2500 CAT vs. COORD	4.86	0.001
				Irrelevant interference	Encoding 250 CAT vs. COORD	7.56	<0.001
					Encoding 500 CAT vs. COORD	3.24	0.008
					Encoding 2500 CAT vs. COORD	3.29	0.007
				Colour interference	Encoding 250 CAT vs. COORD	4.92	<0.001
					Encoding 500 CAT vs. COORD	4.69	0.001
					Encoding 2500 CAT vs. COORD	4.22	0.001
				Silent	Encoding 500 CAT vs. COORD	3.97	0.002
					Encoding 2500 CAT vs. COORD	4.73	0.001
RT							
Encoding × Interference	(6,86)	1.00	0.429				
3 way interaction	(18,258)	0.50	0.957				

Analysis 2: 4-way ANOVA

Spatial relations (CAT and COORD) vs. Encoding times (250ms, 500ms, and 2500ms) vs. Shift sizes (15mm, 20mm, and 25mm) vs. Interference types[*] (Spatial interference, Irrelevant interference, Colour interference, and Silent)

Accuracy	*df*	*F*	*P*	Post-hoc		*t*	*p*
Shift × Interference	(6,88)	0.54	0.777				
Encoding × Interference	(6,88)	0.70	0.653				
Encoding × Shift	(4,176)	1.24	0.298				
Spatial relations × Encoding × Interference	(6,88)	3.16	0.007				
Spatial relations × Encoding × Shift	(4,176)	1.21	0.307				
Spatial relations × Shift × Interference	(6,88)	0.69	0.661				
Encoding times × Shift × Interference	(12,176)	0.33	0.983				
4 way interaction	(12,176)	0.34	0.980				
RT							
Shift × Interference	(6,60)	0.79	0.581				
Encoding × Interference	(6,60)	0.83	0.552				
Encoding × Shift	(4,120)	6.80	*<0.001*	Encoding 500ms	Shift 15mm vs. 20mm	2.70	0.021
					Shift 20mm vs. 25mm	-8.89	<0.001
					Shift 15mm vs. 25mm	-7.42	<0.001
				Encoding 2500ms	Shift 15mm vs. 20mm	3.32	0.007
					Shift 15mm vs. 25mm	2.43	0.033
Spatial relations × Encoding × Interference	(6,60)	0.65	0.694				
Spatial relations × Encoding × Shift	(4,120)	3.94	*0.005*	Encoding 2500ms	Shift 15mm CAT vs. COORD	-2.45	0.019

RT (Cont.)	*df*	*F*	*P*	Post-hoc		*t*	*p*
Spatial relations × Shift × Interference	(6,60)	2.61	*0.026*	Spatial Interference	Shift 15mm CAT vs. COORD	-2.50	0.029
Encoding times × Shift × Interference	(12,120)	3.06	*0.001*	Spatial Interference	Encode 250ms Shift 15mm vs. 25mm	2.90	0.015
				Colour Interference	Encode 250ms Shift 20mm vs. 25mm	3.59	0.004
				Silent	Encode 500ms Shift 15mm vs. 20mm	-2.79	0.018
4 way interaction	(12,120)	1.24	0.266				

N.B. * indicates that the variable (Interference types) is a between-subject variable.

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