THE UNIVERSITY OF HULL

LAMPADA FERENS

Numerical cognition in ageing: Investigating the impact of cognitive ageing on foundational non-symbolic and symbolic numerical abilities

Thesis submitted for the Degree of Doctor of Philosophy, Psychology, at the University of Hull

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September 2015

Acknowledgements

My first thanks go to my fantastic PhD supervisor Dr Julie Castronovo, whose unwavering support and confidence in me has been fundamental in reaching this goal. Thank you for always supporting my ambitions and for being my friend.

Martin- thank you for always being there and believing in me. Your love, constant support and confidence in me mean the world, and more than you'll ever know. I am so proud of the way you, and us as a team, have strongly pushed on, even in the very darkest times.

To my family, you've always just assumed I'd get there in the end, never doubting my ability. Thank you for believing in me and for the various help and advice along the way. I am grateful to Ian for thesis advice, support, and proofreading.

Lydia and Michael, you've made the journey a happy one and I want to thank you for being my PhD buddies. I wish you all the best in the future and fully intend on constant visits.

I will be forever grateful to all of my participants for volunteering their time. Without them, the PhD would not have been possible. Particular thanks go to the older adults from the local community, who volunteered their time to come into the University, and who also assisted in the recruitment of other volunteers by spreading the word and roping in husbands and wives. Your longstanding commitments to taking part in the research are greatly appreciated. Your enthusiasm for the project and willingness to participate in several, and often long testing sessions, made the 650+ hours of participant testing enjoyable.

To everyone at the Department of Psychology, thank you for your friendly welcome. To all the staff; admin, technical and academic, thank you for the chats, support, help, and advice. Particular thanks to Will and Chiara, and to Kevin and Dave for their postdoctoral advice and support.

Thank you to the researchers at the Mathematics Education Centre at Loughborough University for welcoming us to your research group meeting, for listening, and for your valuable advice.

Saffron, Martine, Antonia, and Gareth: thank you for the continued support from the faraway land of Aberystwyth!

Jonathan Esp- thank you for being my coding and vis basic guru!

All of these people and many more have played a massive role in helping me to stay positive and confident throughout the PhD, and have made it an overall fantastic and rewarding experience. Thank you.

Declaration

Parts of this thesis are published, in amended form, in the following research articles:

Norris, J. E., McGeown, W. J., Guerrini, C., & Castronovo, J. (2015). Aging and the number sense: preserved basic non-symbolic numerical processing and enhanced basic symbolic processing. *Frontiers in Cognition*, *6*, 999, http://doi.org/10.3389/fpsyg.2015.00999

Norris, J. E., & Castronovo, J. (under review). Dot Display Affects Approximate Number System Acuity and Relationships with Mathematical Achievement and Inhibitory Control. *PLoS ONE*

Abstract

Healthy ageing is associated with a gradual decline in several cognitive functions, including processing speed, inhibitory control, memory, executive functions, and problem solving. However, the trajectory of ability in numerical cognition in older age remains unclear. Some research investigating exact skills such as arithmetical problem solving have found declined numerical abilities in older age due to reduced access to effective strategies. However, other research has indicated stable or even enhanced mathematical and arithmetical abilities in older age. Furthermore, limited research is available on the impact of ageing on foundational numerical abilities. The effect of cognitive ageing on such foundational abilities poses an interesting question due to the innate, evolutionary nature of foundational numerical skills. It is possible that such automatic, innate and primitive abilities may be spared in ageing, alongside emotional processing, autobiographical memory, and vocabulary and verbal skills.

Available studies investigating basic numerical abilities in ageing present contradictory results and methodological variation. Furthermore, although a limited number of studies have investigated foundational non-symbolic abilities in ageing, the effect of older age on foundational symbolic abilities is yet to be directly tested. The thesis therefore explicitly investigated the impact of healthy ageing on foundational non-symbolic and symbolic numerical processing with a series of experiments. Chapter 2 presents the first study to use classic numerosity discrimination paradigms to compare the non-symbolic and symbolic foundational numerical skills of a group of younger and older adults. Chapter 3 served to further investigate enhanced symbolic numerical abilities in older age found in chapter 2 using a number priming paradigm. The impact of life experience using numbers on foundational numerical skills in older age was studied in chapter 4, whereby older adults with a degree in mathematics were compared with those without explicit further mathematical education. The final two experimental chapters of the thesis examine the reliable measurement of the Approximate Number System in ageing, considering the impact of inhibitory control and mathematical achievement on acuity. Chapter 5 compares non-symbolic acuity in younger and older adults when using either spatially separated or intermixed non-symbolic dot displays. Finally, chapter 6 directly studies the impact of perceptual variables on ANS acuity in ageing, specifically focusing on total cumulative area, dot size, and convex hull (perimeter) congruency.

The series of experiments presented in the thesis indicate that foundational numerical abilities are preserved in healthy ageing. Specifically, non-symbolic numerical abilities remain stable in older age, whereas foundational symbolic abilities are enhanced, possibly due to lifetime exposure to and experience with symbolic numbers. Furthermore, the thesis demonstrates the importance of task design in measuring non-symbolic numerical abilities in ageing, identifying methodological aspects which may lead to poorer acuity in older adults as a result of decline in other cognitive functions (e.g. inhibitory control). The thesis therefore contributes to the literature regarding numerical cognition in ageing, with foundational numerical abilities found to be preserved in healthy ageing. Preservation of such abilities in healthy ageing poses implications for pathological ageing, in that declined foundational numerical skills may serve to indicate pathological processes.

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1 Chapter 1: General introduction

The introduction will seek to outline the current state of research with regards the effect of ageing on numerical cognition, outlining the gap in the literature the thesis seeks to address. Firstly, an introduction to the nature, representation, and measurement of foundational numerical abilities will be presented. Secondly, the effect of ageing on cognition will be introduced, followed by a review of the literature regarding numerical cognition in ageing. Finally, the impact of ageing on other cognitive domains fundamental to performance on numerical tasks will be outlined.

1.1 Foundational numerical abilities

The phrase ‘numerical abilities’ may lead most of us to automatically think of mathematics, counting, calculations, and algebra. However, alongside these exact, procedural numerical abilities, numerosity can be processed at a more foundational and approximate level. In our daily lives we constantly approximate and compare quantities without counting. For example, we are able to decide approximately which of two bags contains more apples, without the need to count out each bag and make a quantity comparison. Such foundational numerical processing can be categorised as non-symbolic or symbolic. A ‘non-symbolic numerosity’ may refer to collections or quantities of items (such as in the example of the bag of apples). A symbolic number refers to cultural symbols attributed to quantities, such as Arabic digits (‘1’) or number words (‘one’). Both non-symbolic and symbolic foundational numerical processing are associated with the ‘Number Sense’ (Dehaene, 1997, 2009; Feigenson, Dehaene, & Spelke, 2004; Verguts & Fias, 2004), and are both thought to play an important role in the acquisition of more advanced numerical and arithmetical skills in early development, such as mathematical achievement (e.g. De Smedt, Verschaffel, & Ghesquière, 2009; Holloway & Ansari, 2009; Piazza et al., 2010). Foundational non-symbolic numerical skills are usually referred to as the Approximate Number System (ANS: Halberda, Mazzocco, & Feigenson, 2008). The ANS is defined as the ability in infants, children, adults, and some animal species to approximate non-symbolic numerical magnitudes without counting, for example when estimating the amount of sweets in a jar, or choosing the shortest queue at the supermarket (Dehaene, 2009; Desoete, Ceulemans, Roeyers, & Huylebroeck, 2009; Feigenson et al., 2004; Gallistel &

Gelman, 2000; Izard, Sann, Spelke, & Streri, 2009; Piazza & Izard, 2009; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004). Although the bag of apples example is a visual approximate quantity, the ANS is thought to be activated in a format-independent and cross-modal manner: participants can simultaneously compare a visually presented and an aurally presented numerosity such as a sequence of tones (Barth, Kanwisher, & Spelke, 2003; Piazza & Izard, 2009), supporting the suggestion that numerosity is represented in an abstract, modality-independent manner (Dehaene, Piazza, Pinel, & Cohen, 2003; but see Cohen Kadosh, Henik, & Rubinsten, 2008). The finding that participants with congenital blindness have superior ANS acuity further supports the modality-independent nature of approximate numerical representations (Castronovo & Seron, 2007). This primitive, non-symbolic, approximate numerical system is thought to be innate, and to have originated from evolutionary systems, due to its presence in animals and detection in early human development (Dehaene, 1997; Feigenson et al., 2004; Park, Park, & Polk, 2012; Piazza & Izard, 2009). When habituated to a non-symbolic numerosity, infants can detect a change in numerosity at a ratio of 2:1, but fail to detect changes at a ratio of 2:3 (Izard, Dehaene-Lambertz, & Dehaene, 2008; Lipton & Spelke, 2004; Starr, Libertus, & Brannon, 2013; Xu & Spelke, 2000). More difficult ratios can be successfully discriminated in later childhood and adulthood (Feigenson et al., 2004; Halberda et al., 2008). Such ratio-dependent performance has also been demonstrated in animals (e.g. rats: Meck & Church, 1983) and non-human primates (e.g. Hauser, Tsao, Garcia, & Spelke, 2003).

The ANS produces two consistently observed behavioural and neuronal markers, demonstrating that approximate numerical processing obeys Weber's law. Weber's law dictates that the threshold for successful discrimination between a pair of stimuli increases linearly with increased stimulus intensity (e.g. increasing loudness of a sound, brightness of a light, etc: Dehaene, 2003; Piazza & Izard, 2009; Piazza et al., 2004). This linearly increasing threshold for discrimination produces ratio and size effects, which are consistently observed during quantity discrimination tasks. The ratio effect refers to slower and less accurate discrimination between two numerosities as their ratio approaches 1, whereas the size effect refers to slower and less accurate responses with increasing magnitude (e.g. Dehaene, 1999; Piazza & Izard, 2009; Roitman, Brannon, & Platt, 2012). The observation of ratio and size effects during numerical processing have been attributed to the representation of numerosity on a 'mental number line' (Dehaene, 1997, 2003). The metaphor of a mental number line is used within the literature to express the manner in which numbers and their corresponding magnitudes are mentally represented, with numbers represented on a continuum from left to right (smaller numbers on the left, with increasing numerosity spreading rightwards (see Figure 1: Verguts & Fias, 2004)). Whether representations on the mental number line are linear or logarithmically compressed is an unresolved issue (e.g. Brannon, Wusthoff, Gallistel, & Gibbon, 2001; Dehaene, Izard, Spelke, & Pica, 2008; Dehaene, 2001, 2003; Gallistel & Gelman, 2000). However, both models yield numerosity representations which overlap with their neighbouring numerical representations. This representational overlap is suggested to account for ratio/distance effects found during numerosity tasks, as when a target number is activated (e.g. '4'), other numerosities close to the activated number on the mental number line will also be somewhat activated ('3' and '5'), with such activation dissipating with distance (Dehaene, 2003; Piazza & Izard, 2009; Piazza et al., 2004). Dehaene (2003) suggested that the work of Nieder and Miller (2003) provides strong evidence at a behavioural and neuronal level of a logarithmic numerical representation in nonhuman primates, with approximate numerosity found to be represented on a non-linear, logarithmically compressed mental number line (Nieder & Miller, 2003). Earlier evidence for such a representation comes from a computational model for numerosity processing created by Dehaene and Changeux (1993), which proposed that individual neurons are approximately tuned to a specific numerosity. Further, the finding of size and ratio effects in neuronal activation in the monkey prefrontal cortex (Nieder, Freedman, & Miller, 2002) supports a logarithmically compressed representation, as logarithmic representations of larger numerosities on the mental number line become 'fuzzier' due to higher levels of overlap compared to smaller numerosities, resulting in the size effect. Finally, similar results have also been demonstrated in the human intraparietal sulcus (Piazza et al., 2004).

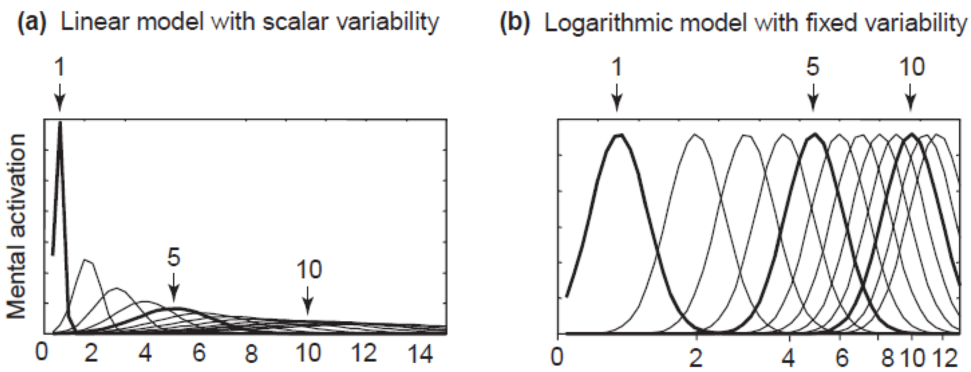

Figure 1: Visual demonstration of the linear vs. logarithmic representation of number (reproduced from Feigenson et al., 2004)

1.1.1 Indexing the approximate number system

In order to measure the precision of an individual's ANS, numerical comparison tasks are most often used. During such tasks, two sets of non-symbolic stimuli (e.g. dots) are displayed briefly on a computer screen, either simultaneously side-by-side, spatially intermixed in two distinctive colours, or sequentially (one set followed by another). Participants must then decide approximately which set is more numerous (see Figure 2). Task difficulty increases (i.e. a participant's accuracy decreases and RTs increase) as the ratio between the to-be-compared numerosities approaches 1, due to the ratio effect (Dehaene, 2003; Piazza & Izard, 2009; Piazza et al., 2004). Alongside accuracy and RT measures, ANS acuity is frequently measured with the Weber fraction (*w*: Halberda et al., 2008). The *w* is calculated using a participant's accuracy scores at each ratio, and indicates the precision of an individual's numerical representation, with a higher *w* indicating a 'noisier' and less precise representation (Halberda et al., 2008; Piazza et al., 2004). Several studies have demonstrated that ANS acuity improves in typical development, reflected by a decrease in *w*, with an average *w* in educated numerate adults of ~ 0.15 (Dehaene, 2009; Halberda & Feigenson, 2008; Halberda et al., 2008; Lipton & Spelke, 2004; Piazza, Pica, Izard, Spelke, & Dehaene, 2013). An individual's Weber fraction should therefore be applicable to any numerosity representation, even those not measured explicitly during the task. The *w* can be mathematically applied to determine the degree of 'fuzziness', or degree of imprecision, in each numerosity representation (Halberda et al., 2008; Halberda & Odic, 2015). The 'fuzziness' of each numerical representation is determined by the width of numerical representation curves, i.e. the standard deviation (SD) of each curve. In Figure 1, an individual with a larger *w* also has a larger numerical representation curve SD. The larger the curves, the more each representation will overlap with neighbouring numerosities, increasing the 'fuzziness' of an individual's numerical representation. For example, the SD of each numerical representation curve for a specific individual with *w* = .15 may be calculated as follows: the SD of the representation curve for '7' (i.e. the width of the curve for 7 and therefore its degree of overlap with nearby numerosity representations) can be calculated by multiplying *w* (.15) with 7, = 1.05 (SD) (see Figure 3; Halberda & Odic, 2015). This calculation demonstrates that a large *w* leads to larger SDs for an individual's numerical representations. Further, the size effect is also demonstrated by increasing SD with increasing numerical magnitude. This method therefore provides a model to understand how an individual with a higher *w* will have poorer numerical representation precision, demonstrating increased sensitivity to both ratio and size effects alongside lower overall accuracy and slower RTs. The approximate number system is therefore demonstrated to consist of a continuum of 'noisy' representations yielding approximate performance. However, although ANS tasks are applied with the aim of measuring individual differences in the acuity of approximate numerical representations, recent literature has demonstrated the possible influence of other cognitive processes such as inhibitory control on performance which may influence acuity outcomes, including *w* (e.g. Clayton & Gilmore, 2014; Fuhs & McNeil, 2012; Gilmore at al., 2013). This issue is further discussed in section 1.3.5.

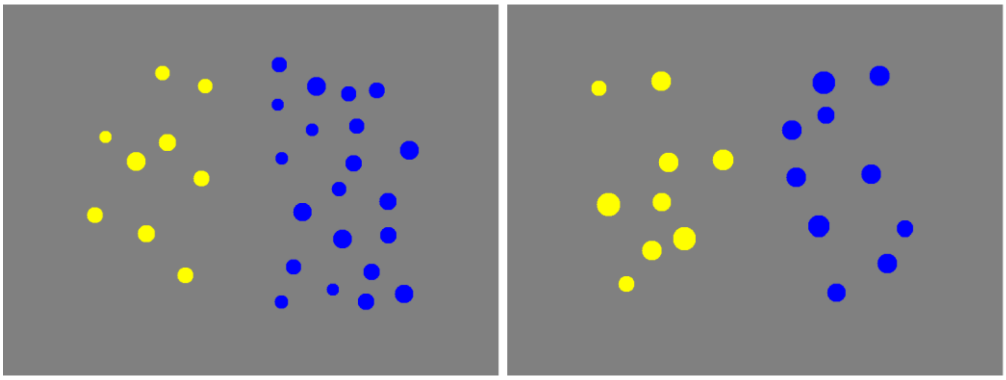

Figure 2: An example of simultaneous stimuli generated during a non-symbolic comparison task: the left image depicts a larger ratio and therefore an easier trial (2.33), whereas the right image depicts a smaller ratio and therefore a more difficult trial (1.11: reproduced from www.panamath.org: Halberda et al., 2008)

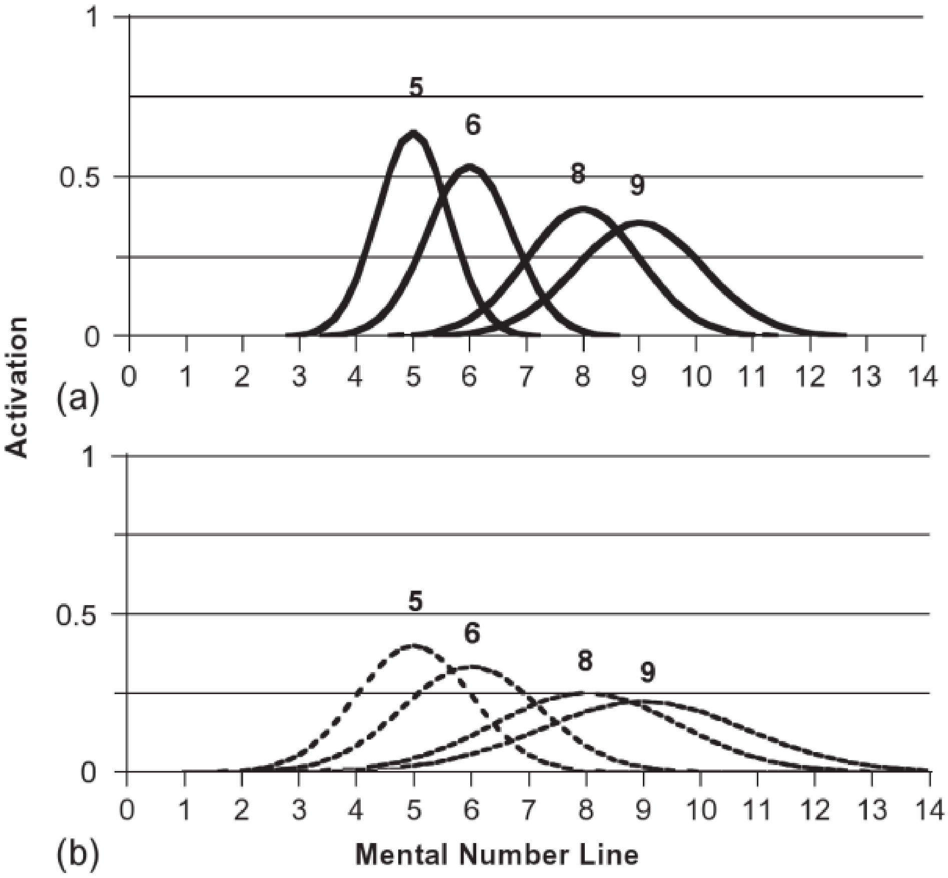

Figure 3: A visual representation of the numerical representations of two people with proposed w$_s$. *The first (image a) has a smaller* w *and therefore less overlap between numerical representations. However, the second (image b) has a larger* w *and therefore a greater degree of representational overlap, and as a result poorer numerical comparison acuity (image reproduced from Halberda & Odic, 2015)*

1.2 The exact number system

Recent literature has mostly focused on non-symbolic, innate, foundational numerical abilities such as the ANS. However, another related system exists: the acquired, symbolic foundational numerical system. Following the acquisition of symbolic numerical knowledge during early education, the ANS is suggested to be progressively refined into a symbolic exact number system (ENS: Castronovo & Göbel, 2012; Dehaene, 2009; Verguts & Fias, 2004). The ENS has been defined as a later-acquired, formal, symbolic, and linear numerical system, which accounts for automatic access between symbolic numbers and their corresponding magnitude (Dehaene, 2009; Verguts & Fias, 2004, but see Verguts & Fias, 2008). The idea of the refinement of the ANS into the ENS with development and acquisition of mathematical knowledge through instruction is supported by behavioural data, such as the observation of an improving precise linear pattern of performance on number line tasks in children with increasing age (e.g. Ashcraft & Moore, 2012; Opfer & Siegler, 2007), and the gradual development of the automatic activation of ENS processing with age during number Stroop paradigms (e.g. Rubinsten, Henik, Berger, & Shahar-Shalev, 2002). Neuroimaging data further support the existence of the ENS alongside the ANS (e.g. Cohen Kadosh et al., 2011), in that the left intraparietal sulcus (IPS) is implicated in processing both non-symbolic and symbolic quantities (Cappelletti, Barth, Fregni, Spelke, & Pascual-Leone, 2007). Further, the innate ANS has been associated with the right IPS and approximate processing of non-symbolic quantities (Dehaene, 2009; Mazzocco, Feigenson, & Halberda, 2011; Siegler & Opfer, 2003), and the acquired ENS with the left parietal lobe and symbolic number processing (Ansari, Dhital, & Siong, 2006; Cantlon, Brannon, Carter, & Pelphrey, 2006; Izard, Dehaene-Lambertz, & Dehaene, 2008; Piazza, Pinel, Le Bihan, & Dehaene, 2007; but see Cappelletti, Lee, Freeman, & Price, 2010). This evidence supports the notion of an approximate numerical system, supporting the approximate representation of both non-symbolic and symbolic quantities. As with the ANS, ENS processing obeys Weber's law. However, the ENS is suggested to be more precise, producing less pronounced distance and size effects than non-symbolic stimuli (e.g. Buckley & Gillman, 1974). It is emphasised however that the ENS is differentiated from procedural numerical abilities such as mathematical calculation, in that the ENS is responsible for basic, foundational processing of symbolic numbers. Therefore, mathematical processing is not required to be engaged, for example, when judging which of two symbolic numbers is largest. This decision is made in an approximate, distance-dependent manner, analogous to ANS processing.

1.3 Cognitive ageing

Healthy ageing, as opposed to pathological ageing caused by disease (e.g. dementia), is associated with decline in a variety of cognitive domains. Healthy ageing is generally understood to result in poorer fluid intelligence, dictating an individual's ability to effectively and efficiently solve new problems. This age-related decline in fluid intelligence includes reduced speed of processing, poorer memory, reasoning, and executive functions (Christensen, 2001; Deary et al., 2009; Hedden & Gabrieli, 2004; Salthouse, 1996, 2009), and a reduction in an older adult's ability to inhibit irrelevant but competing and distracting information (Hasher & Zacks, 1988; Hedden & Gabrieli, 2004; Kramer, Humphrey, Larish, &

Logan, 1994). A linear decline in speed of processing with increasing age may account for deterioration observed in other faculties, such as poorer working memory (Deary et al., 2009; Hedden & Gabrieli, 2004; Salthouse & Kersten, 1993; Salthouse, 1996). However, results from both cross-sectional and longitudinal studies of ageing participants (Christensen, 2001) suggest that forms of crystallised intelligence (i.e. a culmination of individual knowledge: Christensen, 2001), such as verbal, numerical, and general knowledge abilities, as well as autobiographical memory and emotional processing (Hedden & Gabrieli, 2004), are robust to cognitive ageing, with education and higher childhood intelligence providing a further protective effect against age-related decline in such abilities (Christensen, 2001; Deary et al., 2009). In terms of the neurology of the ageing brain, general brain volume decreases, cerebro-spinal fluid surrounding the brain increases, and ventricles and sulci increase in size. Furthermore, white matter loss reduces global cerebral connectivity, contributing to declined higher order cognitive abilities (e.g. executive function: Deary et al., 2009), as well as slower processing speeds, and poorer memory and reasoning abilities in older age (Hedden & Gabrieli, 2004), with the trajectory of cerebral matter decline suggested to follow an anterior to posterior gradient (Deary et al., 2009). Many environmental and genetic factors have been proposed to either reduce or exacerbate normal cognitive decline in older age, including genetics, vascular disease, poor health, high blood pressure, inflammation, diet, and exercise (Christensen, 2001; Deary et al., 2009; Hedden & Gabrieli, 2004). However, aside from the effect of cardiovascular disease and diet, the significance of each factor in cognitive ageing remains disputed and unclear. What is clear however is that research into the causes and nature of normal cognitive ageing is crucial, as cognitive decline, hand-in-hand with an ever-increasing ageing population, places a large burden on care services and the state more widely (Deary et al., 2009). Therefore, a clearer understanding of the changes to be expected with ageing provides a better appreciation of which changes may be normal, and which may indicate pathological processes. Improved understanding of normal cognitive ageing also enhances contrast between normal and non-normal ageing, assisting in the early detection of changes potentially indicating pathological processes.

It is well known that average life expectancy is steadily increasing. According to UK Government statistics, in 1951 a 65 year old man could expect on average to live to the age of 77 (UK Government, 2015). In 1981, average life expectancy for a man increased by 7 years to 84 (Cracknell, 2010), and today, a man can expect to live to 86, and to 91 by 2050. Such a rise in average life expectancy inevitably leads to a broadly ageing population.

Currently in the UK there are 15,000 people who are aged 100 years or over (UK Government, 2015). Furthermore, 10 million people in the UK are aged over 65, and it is predicted that this figure will increase by an additional 5.5 million by 2035, with the number almost doubling to approximately 19 million by 2050 (Cracknell, 2010). Although our total life*span* is rising dramatically, this has not correlated with an increased *healthy* life expectancy. The rise in the number of older adults in the population, many of whom may not be ageing healthily, results in a proportionate increase in demand on public services, particularly the NHS (Cracknell, 2010; Deary et al., 2009). Alongside a drive to promote healthy living across the lifespan, the UK Government proposes to support the ageing population by increasing opportunities to retrain and stay in work longer, increasing volunteering opportunities for the retired population, and encouraging the entire community to work together in facilitating independent living in older age (UK Government, 2015). These policies are interlinked with the global initiative on ageing, which proposes ten commitments to encourage a thriving global older population. The below commitment is most pertinent to the thesis:

> *"...to ensure quality of life at all ages to maintain independent living including health and wellbeing" (United Nations, 2002, p.33)*

The commitment central to the above quote details the necessity for early intervention in preventing and delaying the onset of age-related disease, and for the development of reliable indicators of common diseases to detect and prevent further illness in ageing. Therefore, prevention, timely detection, and early intervention are key policies within the agreement. Without a clear understanding of cognitive changes to be expected in healthy ageing, it may be difficult to determine which changes may constitute pathological ageing processes. In particular, the agreement stresses the importance of further research developing quality assessments for Alzheimer's disease and similar disorders (i.e. dementia) at an earlier stage than is commonly achieved (United Nations, 2002). It is crucial therefore to gain a clear understanding of the effect of *healthy* ageing on cognition, in order to achieve a clear comparison between changes normally expected in healthy ageing, and those associated with pathological processes such as dementia.

1.3.1 Numerical cognition in ageing

Although much is understood about the effect of normal ageing on cognitive domains such as memory, executive functions, attention, and reasoning, the literature regarding numerical abilities in ageing is more limited. Further, both foundational non-symbolic and symbolic numerical abilities have primarily been studied in children and young adults. Therefore, the impact of healthy ageing on these two foundational numerical systems is not well known. Further investigation of this issue is of clear importance, notably considering evidence that although some numerical capacities are thought to be preserved in ageing (Deary et al., 2009; Hedden & Gabrieli, 2004), structural changes such as grey matter atrophy and a decline in the regional cerebral metabolic rate for oxygen in the parietal lobes (for a review see Dennis & Cabeza, 2008) are correlated with healthy ageing. These cortical areas play a crucial role in foundational numerical skills (Cappelletti et al., 2007, 2010; Piazza & Izard, 2009; Piazza et al., 2004, 2007; Roitman et al., 2012; Sasanguie, Göbel, & Reynvoet, 2013). So far, it is unclear whether these neurological changes manifest behaviourally in terms of older adults' basic numerical abilities. Studies in the field of numerical cognition and ageing have mostly investigated high-level mathematical skills, such as counting, arithmetic problem solving, and strategies for quantification (e.g. Duverne & Lemaire, 2004; El Yagoubi et al., 2005; Gandini, Lemaire, & Dufau, 2008). More recently, a handful of studies have investigated foundational skills, such as non-symbolic numerosity discrimination (Cappelletti et al., 2014; Dormal, Grade, Mormont, & Pesenti, 2012; Halberda, Ly, Wilmer, Naiman, & Germine, 2012; Li et al., 2010). However, results are contradictory, and therefore no clear conclusion can yet be drawn on the effect of ageing on these basic numerical skills (see below 1.3.2). Moreover, the question of the effect of ageing on foundational *symbolic* numerical skills has yet to be directly addressed.

1.3.2 Symbolic numerical abilities in ageing

Research on the effect of ageing on symbolic numerical skills has mainly focused on exact, complex abilities such as arithmetical problem solving (e.g. Duverne & Lemaire, 2004; Lemaire & Arnaud, 2008). In an early study on ageing and symbolic numerical processing, Salthouse and Kersten (1993) trained older and younger adults to recognise abstract symbols as the digits 1 to 9. The older group made fewer errors than the younger group in an arithmetic task using Arabic digits, but recognised the new symbols as digits less accurately than the younger adults. These results were attributed to a speed of processing decline in ageing rather than to deteriorated arithmetical skills (Salthouse & Kersten, 1993). However, when investigating the effect of ageing on simple (single digit) and complex (three-digit numbers) arithmetical problem solving, Duverne and Lemaire (2004) found that arithmetic accuracy and the ability to choose the correct strategy for each problem declines in older age, especially with more complex problems. It has been suggested that older adults may have a smaller repertoire of strategies to solve arithmetic problems and poorer efficiency in selecting and switching between effective strategies for each problem (Duverne & Lemaire, 2004; Lemaire & Arnaud, 2008; Uittenhove & Lemaire, 2015). This is supported by Event Related Potentials (ERP) data demonstrating a left hemisphere advantage in younger adults during an arithmetic problem-verification task which is reduced in the older group (El Yagoubi et al., 2005). It is possible that the number of potential strategies for problem-solving may be reduced in the older group, whereas younger adults may be more able to flexibly choose the most effective strategy for each problem from a wider repertoire (El Yagoubi et al., 2005; Uittenhove & Lemaire, 2015). Conversely, different patterns of neuronal activation during the same task in younger and older adults may result from a failure by the older group to inhibit interfering information (Hedden & Gabrieli, 2004). Alongside the study of high-level arithmetic skills in ageing, basic symbolic numerical skills were briefly investigated by Cappelletti et al. (2014). Older and younger participants took part in a symbolic comparison task on single digit numbers (1 – 9) as part of a battery of arithmetical tasks. Participants decided whether the number presented to the left or right of the screen was the largest. The results of this task seem to show no difference between older and younger adults in terms of comparison accuracy, but reveal slower performances for the older group. Geary and Lin (1998) proposed that the slowing effect of ageing on numerical cognition may differ depending on the nature of the numerical ability, either primary or secondary. Primary abilities are suggested to stem from processes unrelated to education, likely preserved due to evolutionary functioning (e.g. 'subitizing'; the processing of between 1 and 4 items is error-free and fast: Dehaene, 1992; Gallistel & Gelman, 1992; Trick & Pylyshyn, 1994), whereas secondary abilities are suggested to be primarily built upon learned, cultural abilities, such as the attribution of symbols to numerical quantities (e.g. complex subtractions: Geary & Lin, 1998). In order to test this hypothesis, Geary and Lin (1998) compared the performance of a group of younger and older adults on a range of numerical tasks categorised as being either primary or secondary. Of particular interest to the authors were subitizing and complex subtraction performance, both assumed to represent the purest forms of primary and secondary abilities respectively. Geary and Lin's (1998) findings support the suggestion of slowed processing speed in ageing (Salthouse, 1996), but not to the same degree for all numerical processes. The authors concluded that age-related decline in speed of executing numerical skills was more apparent during primary processing (e.g. subitizing), compared to secondary processing (e.g. mathematics). Such findings were suggested to support an age-related decline in primary abilities, whereas secondary abilities may be protected in ageing due to cohort effects. Better mathematical knowledge in the older group was suggested to potentially mask declined abilities in older age. Although this study provided the groundwork for the investigation of foundational and exact numerical abilities in ageing, it posed conflicting conclusions. Firstly, symbolic comparison performance on a single-digit task (as in Cappelletti et al., 2014) was found to be similar between groups beyond the small-number (1-4) range. Such preservation of larger-magnitude comparison in ageing was considered as a preserved secondary ability, although symbolic comparison represents an automatic process (i.e. ENS: Castronovo & Göbel, 2012). Preservation of symbolic comparison may therefore constitute a preserved foundational, primary ability. No clear conclusion can be drawn from these early findings on basic symbolic numerical skills in ageing, notably because of the use of a small numerical range which, considering the task's low level of difficulty, may not allow clear dissociation between age groups (Lonnemann, Linkersdörfer, Hasselhorn, & Lindberg, 2011). Furthermore, research on more procedural symbolic numerical skills in ageing has revealed mixed results, with some suggesting a decline in such abilities (e.g. Duverne & Lemaire, 2004; Lemaire & Arnaud, 2008), and others finding no impact of ageing, or even superior symbolic skills in older adults (Cappelletti et al., 2014; Salthouse & Kersten, 1993). Moreover, the majority of studies have focused on higher-level symbolic numerical skills, such as arithmetic problem solving, neglecting foundational symbolic abilities. Therefore, the question of the impact of ageing on foundational symbolic numerical skills is still very much open and requires further investigation (Uittenhove & Lemaire, 2015) using a classic symbolic numerical task with a large enough numerical range to allow discrimination between younger and older participants' ENS acuity (i.e. two-digit stimuli: Moyer & Landauer, 1967; Nuerk, Weger, & Willmes, 2001).

1.3.3 Non-symbolic numerical abilities in ageing

A limited number of studies have investigated basic non-symbolic numerical processing in ageing, although methods and stimuli have varied widely, with some contradictory results. Firstly, some research has suggested a deterioration of basic non-symbolic numerical processing with age. Trick, Enns and Brodeur (1996) studied the effect of ageing on basic non-symbolic numerical skills with series of speeded quantity discriminations: 1 vs. 2, 3 vs. 4, 6 vs. 7, and 8 vs. 9. Participants indicated as quickly as possible whether two arrays presented for up to 7,800ms contained an equal number or *n*+ 1 dots. In the subitizing range, the results suggest no decline in quantity discrimination skills with age. However, older participants performed more slowly than younger adults beyond the subitizing range. Moreover, further consideration of the results on accuracy presented in Figure 4 (Trick et al., 1996, p.928) indicates higher accuracy in the older compared to the younger group for the larger quantity discrimination range, possibly reflecting a speed-accuracy trade-off. On the contrary, Watson, Maylor, and Bruce (2005) found similar enumeration performance of between 1 and 9 'Os' in older and younger adults in both subitizing and counting ranges. However, when distracters were added, enumeration speed decreased for the older group only, possibly due to increased visual fixations for older adults in distracter-trials compared to those without distracters (Watson et al., 2005). Whilst studying estimation skills on small (20-39) and large (40-65) non-symbolic numerosities in healthy and pathological ageing (Alzheimer's disease: AD), Gandini, Lemaire and Michel (2009) showed that healthy ageing is associated with poorer estimation speed but not accuracy, concluding that slower estimation in ageing could reflect a decline in processing speed (Salthouse, 1996) rather than deteriorated numerical abilities. However, lower accuracy for older compared to younger adults on estimating numerosities between 4 and 79 supports the suggestion of a negative impact of ageing on non-symbolic quantity processing (Gandini et al., 2009). In view of these initial, somewhat contradictory data, no clear conclusion can be drawn on whether basic non-symbolic numerical processing is preserved or declined in ageing. Further, long stimulus displays used in the studies discussed may have encouraged enumeration, rather than reliably measuring automatic, approximate numerosity processing.

More recently, some authors have begun to study non-symbolic numerosity processing in ageing using brief stimulus presentation times. Li et al. (2010) submitted older and younger participants to an estimation task on a small range (1-9), in which target numerosities were presented for 200ms. The authors found that ageing appears to be associated with poorer performance, with older adults presenting slower RTs and greater response variability than younger adults. However, since both groups presented similar accuracy overall, the authors suggested that older participants' slower performance and higher response variability in small numerosity estimation may be better accounted for by deteriorated peripheral cognitive processes, such as spatial selective attention and visual memory, rather than by an explicit decline in numerical abilities. In a large-scale online study including more than 10,000 participants aged between 11 and 85, Halberda et al. (2012) studied ANS acuity across the life-span with the 'Panamath' paradigm. Their results suggest a decrease in ANS acuity throughout adulthood (increased *w*) from around age 30, with the highest w_s in older adults aged over 60. However, the authors did not further discuss this apparent age-related decline in ANS acuity.

Whilst some research suggests age-related deterioration in foundational non-symbolic numerical skills, other studies indicate that such skills may be resilient to ageing. Lemaire and Lecacheur (2007) investigated the effect of ageing on approximation, with eye-movements recorded as younger and older adults estimated the numerosity of large sets of dots (40 - 460). Stimuli remained on-screen until response for up to six seconds. Results showed similar accuracy but different eye-movement patterns between groups. Older participants made more numerous but shorter fixations and scanned stimuli more broadly than younger participants. The authors suggested that older adults may use compensatory strategies during estimation to negate the impact of deteriorated vision. Further, such eye-movement patterns suggest that participants were likely using counting strategies rather than approximation. Dormal et al. (2012) investigated numerosity and duration processing in healthy ageing and Parkinson's disease (PD). They used a numerosity comparison task in which participants compared two series of flashing dots, ranging from 5 to 9, and a duration comparison task in which participants compared two successive sets of flashing dots varying in duration. Although older adults made more errors during the duration comparison task, there was no effect of healthy or pathological ageing (PD) on numerosity comparison, with older, younger, and PD participants performing similarly. Further, Lambrechts, Karolis, Garcia, Obende, and Cappelletti (2013) studied spatial and duration processing in younger and older adults using comparison and bisection tasks of continuous quantity, including length and duration. Lambrechts et al. (2013) concluded that continuous quantity processing skills may be resilient to ageing due to their primitive basis (i.e. their appearance very early in development). Finally, a recent study directly investigated the impact of ageing on non-symbolic numerical processing. In order to study whether ageing was associated with refined or deteriorated basic numerical skills, Cappelletti et al. (2014) compared older and younger participants' performance on a non-symbolic quantity discrimination task, similar to that of Halberda et al. (2012). Their results showed a larger mean *w* for older adults, initially suggesting poorer ANS acuity in ageing. However, further analyses revealed that this age difference was only present during trials requiring participants to inhibit perceptual information incongruent with numerosity (i.e. an incongruent trial). The authors therefore concluded that the observed decline in ANS acuity in ageing may be accounted for by impaired inhibitory skills (Hasher & Zacks, 1988) rather than a decline in numerical skills. It is therefore clear that a requirement for inhibition during ANS tasks using congruent and incongruent trials (Clayton & Gilmore, 2014; Fuhs & McNeil, 2013; Gilmore et al., 2013; Szűcs, Nobes, Devine, Gabriel, & Gebuis, 2013) may affect ANS acuity measures, particularly in older adults due to their reduced inhibitory control (Cappelletti et al., 2014; Hasher & Zacks, 1988; Kramer et al., 1994).

1.3.4 Inhibitory control in ageing

A reduced ability to inhibit irrelevant but distracting information has been suggested to account for effects of ageing on several aspects of cognition, termed the 'Inhibitory Deficit Theory' (Hasher & Zacks, 1988). Older age is suggested to be associated with deteriorated inhibitory control, particularly in terms of a declined ability to suppress irrelevant information (Connelly & Hasher, 1993; Hasher, Stoltzfus, Zacks, & Rypma, 1991; Hasher & Zacks, 1988; Kramer et al., 1994; Lustig, Hasher, & Zacks, 2007). Reduced inhibition in older age is further supported by the finding that older adults persistently failing to demonstrate negative priming (an effect of inhibiting a target due to its previous appearance as a distracter: Andrés, Guerrini, Phillips, & Perfect, 2008; Hasher et al., 1991; Kramer et al., 1994). The significance of reduced inhibitory control in ageing to other cognitive functions remains somewhat debated. Indeed, it is suggested that a direct measure of the impact of inhibition on cognition in ageing cannot be achieved without consideration of other age-related declines, such as reduced speed of processing (Borella, Carretti, & De Beni, 2008; Salthouse & Meinz, 1995; Verhaeghen & De Meersman, 1998). However, several studies have found robust effects of poorer inhibitory control in older age, even when controlling for cognitive slowing (e.g. Troyer, Leach, & Strauss, 2006). Indeed, it has been conversely argued that declined inhibitory control may *account* for slower processing speed in older adults (Lustig et al., 2007). However, the importance of deteriorated inhibitory control in ageing is well-recognised, and continues to be cited as a key factor within ageing cognition research (Dempster, 1992). Age-related decline is found within specific inhibitory functions (Kramer et al., 1994), particularly executive inhibition, which requires higher levels of effortful, attentive inhibition (Andrés et al., 2008). Kramer et al. (1994) found evidence for weak associations between several tasks purporting to measure inhibition (e.g. the Wisconsin Card Sorting task, Stop-Signal task, Stroop task, negative priming, etc), supporting the notion of inhibitory control as an umbrella term for a variety of unitary constructs of inhibition (e.g. Friedman & Miyake, 2004). Poor correlation between tasks may reflect different levels of requirement for each inhibitory function during the different tasks (e.g. deletion vs. stopping an inappropriate response: Lustig et al., 2007). Task invariance is further supported by neuroimaging data, demonstrating different areas of activation for tasks measuring multiple facets of inhibition (Nee, Wager, & Jonides, 2007).

Although many types of inhibitory control have been discussed, this section will focus on those most pertinent to numerical cognition in ageing, namely interference control and the ability to suppress an overt but inappropriate response in favour of a more effective response to task demands (Lustig et al., 2007; Nigg, 2000). Interference control has been postulated as a necessary cognitive step during ANS tasks using congruent and incongruent trials, as interference from dot size on some trials must be inhibited to effectively respond to numerosity (this is further discussed in section 1.3.5: Clayton & Gilmore, 2014; Fuhs & McNeil, 2013; Gilmore et al., 2013; Szűcs et al., 2013). Moreover, ageing is thought to particularly affect the capacity to inhibit an overt behavioural response (Kramer et al., 1994). Indeed, age-related decline is consistently found for performance on Stroop tasks, and go/no-go measures of inhibition, whereby participants must suppress a salient but inappropriate response (Cappelletti et al., 2014; Girelli, Sandrini, Cappa, & Butterworth, 2001; Lambrechts et al., 2013; West & Alain, 2000). The Stroop effect measure of inhibitory control can also be administered in numerical format using the 'number Stroop' paradigm (Cohen Kadosh et al., 2008; Tzelgov, Meyer, & Henik, 1992). In the number Stroop paradigm, pairs of single digit Arabic numerals are presented, and participants must make a 'which is larger' judgement based on either the magnitude or the physical size of presented Arabic digits. Trials can be neutral, congruent and incongruent (see Table 1). Participants therefore experience interference effects during incongruent trials and facilitation effects during congruent trials (Cohen Kadosh et al., 2008; Girelli et al., 2001; Tzelgov et al., 1992). Research applying the number Stroop paradigm in ageing demonstrates higher interference and lower facilitation effects in older compared to younger adults (Cappelletti et al., 2014; Girelli et al., 2001; Lambrechts et al., 2013). Finally, this inhibitory deficit in healthy older adults is further exacerbated in Alzheimer's disease (e.g. Girelli et al., 2001).

Table 1: An illustration of trial congruency during a number Stroop task

Neutral	Congruent	Incongruent
Magnitude task: the physical size of the stimuli is constant (2 6) *Physical* task: two identical Arabic digits in different physical sizes (6 6)	The larger Arabic digit in terms of magnitude would also be the physically larger digit (2 6)	The larger digit in terms of magnitude would be physically the smallest (2 6)

An age-related deficit in inhibiting an overt response is therefore particularly important to older adults' ANS task performance. As a result of their reduced ability to inhibit an overt response (i.e. responding to the salient dot size), older adults may show a deficit in terms of selectively attending to numerosity whilst simultaneously inhibiting an incorrect response to dot size during incongruent trials (e.g. Cappelletti et al., 2014). As previously stated, in the first study to directly compare ANS acuity between a group of younger and older adults, Cappelletti et al. (2014) initially found an increased *w* (poorer precision of numerical representation) in the older compared to the younger group. However, once performances were analysed in terms of congruent and incongruent trials, it became clear that the older group's observed decline in ANS acuity was driven by poorer performance during incongruent trials. Moreover, this poorer performance was related to older adults' higher interference effects on measures of inhibitory control (e.g. number Stroop). Cappelletti et al. (2014) concluded that ANS acuity remains stable in older age, but may appear to be declined due to poorer performance on trials requiring the inhibition of an overt response to dot size. Poorer performance by older adults on such trials was therefore concluded to be driven by older adults' declined inhibitory control (Cappelletti et al., 2014; Hasher & Zacks, 1988), rather than reflecting deteriorated ANS acuity in ageing. In a further study, Cappelletti, Pikkat, Upstill, Speekenbrink, & Walsh (2015) aimed to extend the investigation of the role of inhibitory control and cue integration (i.e. integrating multiple cues from the stimulus set, such as numerosity, dot size, area, etc) for ANS task performance in ageing. Using parietal, sham, or control Transcranial Random Noise Stimulation (tRNS), younger and older adults received several ANS training sessions, with acuity measured at pre- and post-training, and at 16 weeks follow-up. Whilst all participants receiving parietal tRNS demonstrated improved ANS acuity, in the younger group such improvement applied to both congruent and incongruent trials, and was further related to improved discrimination of continuous quantities such as time and area. The authors concluded that the younger group had learned via training with parietal tRNS to better integrate visual cues during the ANS task to achieve a correct response. On the other hand, improved ANS acuity in the older group was driven by better performance during incongruent trials, which was further related to improved inhibitory control. However, this resulted in poorer area and time discrimination in the older group, possibly due to participants' reinforced learning to inhibit continuous properties during the numerosity task (Cappelletti et al., 2015). These results therefore further support the crucial role of inhibitory control during ANS tasks, and the consequences of declined inhibition in older age on the reliable measurement of foundational numerical abilities. As inhibitory control has been demonstrated to affect the measurement of ANS acuity in both younger (Clayton & Gilmore, 2014; Fuhs & McNeil, 2013; Gilmore et al., 2013; Szűcs et al., 2013) and older adults (Cappelletti et al., 2014, 2015), the concurrent measurement of inhibitory abilities alongside foundational numerical abilities is required. Measurement of inhibitory control will therefore provide an additional facet of analysis throughout the thesis in terms of comparing the foundational numerical abilities of younger and older adults, and will assist in more reliably determining the trajectory of such abilities in healthy ageing.

1.3.5 Inhibitory control during ANS tasks

An important factor currently under considerable debate with regards to the measurement of ANS acuity is the contribution of inhibitory control. In order to ensure that participants make a judgement based on numerosity, rather than on other perceptual variables which correlate with numerosity (e.g. average dot size, total cumulative surface area of the dot sets: Gebuis & Reynvoet, 2012a, 2012b; Leibovich & Henik, 2013; Szűcs et al., 2013; but see Halberda, Mazzocco, & Feigenson, 2008), dot size and surface area controls have been introduced for tasks measuring the ANS. For example, when two dot arrays varying in numerosity are displayed simultaneously, the more numerous set will also have the largest total cumulative area and a larger average dot size. Therefore, participants are able to make a 'which is most numerous' judgement based on perceptual variables alone (e.g.

larger blue dots), without engaging directly in a numerosity judgement. In order to address such concerns, and to ensure that participants engage the numerosity system during an ANS task, researchers have used a variety of methods to control dot size (Abreu-Mendoza, Soto-Alba, & Arias-Trejo, 2013; Leibovich & Henik, 2013). In designing their non-symbolic numerosity discrimination paradigm 'Panamath', whereby participants decide which of two sets of dots (blue and yellow) is most numerous, Halberda et al. (2008) defined three ways in which perceptual variables may be controlled. The stimuli may be congruent, incongruent, or anticorrelated (see Table 2 & Figure 4).

Table 2: An explanation of dot size controls and their congruency status

Congruent	**Incongruent**	**Anticorrelated**
The most numerous array will also have the largest surface area and average dot size. Numerosity correlates with dot size and area.	Total cumulative area of each dot set is equal, regardless of numerosity. The more numerous set has smaller dots on average. Numerosity correlates negatively with dot size and does not correlate with area.	The most numerous dot set will have the *smallest* total surface area. Numerosity negatively correlates with dot size and area.

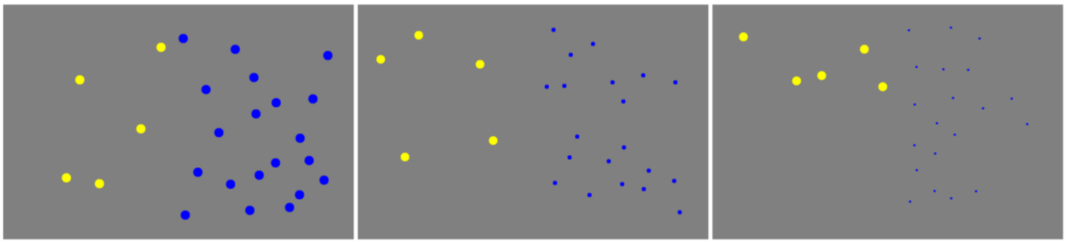

Figure 4: Examples (from left to right) of congruent, incongruent, and anticorrelated ANS trials (reproduced from Halberda et al., 2008)

To summarise, the perceptual variables of total cumulative area and average dot size only correlate positively with numerosity during congruent trials. During both incongruent and anticorrelated trials, dot size negatively correlates with numerosity, and only during anticorrelated trials do both dot size and cumulative area correlate negatively with numerosity. Therefore, both incongruent and anticorrelated trials could be considered as 'incongruent', in that dot size is incongruent to numerosity. However, which of these congruency conditions have been used throughout the literature has varied (Clayton &

Gilmore, 2014; Smets, Sasanguie, Szűcs, & Reynvoet, 2015), with most including congruent and incongruent trials. However, the use of congruent vs. incongruent or anticorrelated trials in measuring the ANS has been suggested to present a Stroop-like effect (Abreu-Mendoza et al., 2013; Clayton & Gilmore, 2014; Fuhs & McNeil, 2013; Gilmore et al., 2013; Szűcs et al., 2013), in that during 'incongruent' trials the irrelevant and incongruent but salient dot size must be inhibited to judge numerosity. It is therefore suggested that ANS tasks, due to the nature of perceptual variable congruency and its manipulation, may indeed measure participants' inhibition skills (Clayton & Gilmore, 2014; Gilmore et al., 2013). Further evidence for such a suggestion comes from studies identifying a correlation between performance on incongruent trials and interference effects derived from inhibitory control tasks (Cappelletti et al., 2014, 2015; Clayton & Gilmore, 2014; Fuhs & McNeil, 2013; Gilmore et al., 2013). Moreover, some authors have suggested that where a correlation is found between mathematical achievement and ANS acuity, this may be driven by a link between mathematical ability and the inhibition component of the ANS task (Bull & Scerif, 2001; Clayton & Gilmore, 2014; Fuhs & McNeil, 2013; Gilmore et al., 2013; St Clair-Thompson & Gathercole, 2006). Further discussion and testing of the relationship between ANS acuity, inhibition, and mathematical achievement is presented in chapters 5 and 6.

1.4 Aims of the thesis

As a result of sparse literature and variable methods, a clear conclusion cannot be drawn on the impact of ageing on foundational numerosity processing. In terms of non-symbolic abilities, the use of long presentation times in some studies is problematic, as counting strategies may have been encouraged. Therefore, these studies have likely measured the effect of ageing on counting abilities rather than approximate, foundational non-symbolic numerical processing (e.g. Gandini et al., 2008; Lemaire & Lecacheur, 2007). Others have not controlled for continuous perceptual variables such as the size and cumulative area of stimuli (e.g. Gandini et al., 2008). Furthermore, the contribution of other cognitive functions such as inhibitory control to ANS acuity in ageing remains unclear (Cappelletti et al., 2014, 2015; Uittenhove & Lemaire, 2015). Most research has also focused on a single measure to assess ANS performance (e.g. percentage correct in Lemaire & Lecacheur, 2007; *w* in Cappelletti et al., 2014). Finally, in Halberda et al.'s (2012) study suggesting declined ANS acuity in ageing, trials requiring inhibitory control were not directly addressed, which may explain why the findings contradict those of Cappelletti et al. (2014). The thesis aims to directly address these issues in order to gain a clearer understanding of the impact of ageing on foundational non-symbolic numerical skills. This will be achieved by using short presentation times to clearly measure numerosity discrimination skills, whilst analysing the effect of dot-size congruency to further dissociate between impoverished numerosity skills and reduced inhibitory control in older age (Cappelletti et al., 2014, 2015). Further, three measures of ANS acuity will be analysed to assess the global impact of ageing on the ANS (accuracy, RTs and *w*: Halberda et al., 2008). Moreover, the impact of ageing on foundational symbolic numerical skills has yet to be directly addressed. Therefore, the thesis will also seek to investigate whether ageing and its resultant life-long exposure to numbers is associated with refined or impaired foundational symbolic numerical skills. Prior research into symbolic numerical processing in ageing has most often investigated exact abilities such as arithmetic and mathematical problem solving. Where symbolic numerical abilities have been compared in younger and older adults (Cappelletti et al., 2014; Geary & Lin, 1998), a small numerical range has restricted the ability to discriminate between participants' performances, and the results from the task have not been directly discussed in terms of the preservation or decline of foundational symbolic numerical abilities in ageing. The thesis therefore aims to directly study the impact of ageing on foundational symbolic skills using a variety of tasks, including a two-digit symbolic comparison task. Finally, with a series of experiments the thesis will seek to determine the most reliable method of measuring ANS acuity in ageing.

1.4.1 Research questions

1- How are foundational non-symbolic and symbolic numerical abilities affected by healthy ageing?

2- How can foundational non-symbolic numerical abilities be measured reliably in ageing?

2 Section 1: Foundational numerical abilities in ageing

In this first section, the thesis aims to investigate the effect of healthy ageing on foundational non-symbolic and symbolic numerical abilities. The section is split into three chapters. Chapter 2 consists of the first study to directly investigate the impact of healthy ageing on both foundational non-symbolic and symbolic numerical abilities. This study compared a group of younger and older adults' acuity in discriminating the largest of either sets of dots or Arabic digits, whilst also controlling for mathematical achievement and general cognitive ability. Chapter 3 aims to further develop the findings from chapter 2 by continuing the direct investigation of symbolic numerical representations in ageing using a number priming task. Finally, chapter 4 presents a study comparing the older adults from chapter 2 with an additional group of older adults with a higher education in mathematics. The aim of chapter 3 was to further investigate the role of mathematical education and achievement on the trajectory of non-symbolic and symbolic ability in ageing. These chapters are followed by section 2, which will seek to investigate the valid and reliable measurement of foundational non-symbolic numerical abilities in ageing, with a focus on the impact of methodological variations on ANS acuity outcomes.

3 Chapter 2: Foundational non-symbolic and symbolic numerical processing in ageing

3.1 Declaration

This chapter is reproduced in an amended form as a research article:

Norris, J. E., McGeown, W. J., Guerrini, C., & Castronovo, J. (2015). Aging and the number sense: preserved basic non-symbolic numerical processing and enhanced basic symbolic processing. *Frontiers in Cognition*, *6*, 999. http://doi.org/10.3389/fpsyg.2015.00999

3.2 Introduction

The current study aims to investigate the effect of healthy ageing on foundational numerical processes, by assessing basic non-symbolic and symbolic numerical skills in a group of healthy older adults compared to younger adults with the use of classic non-symbolic and symbolic numerical comparison tasks. It is currently unclear whether basic numerical abilities remain intact in ageing, similar to semantic knowledge, vocabulary, and reasoning (Hedden & Gabrieli, 2004; Salthouse, 2009), or decline as do working and episodic memory, attention, and executive processes (Deary et al., 2009; El Yagoubi et al., 2005; Lemaire & Lecacheur, 2007; Salthouse, 2009). Numerical cognition in healthy ageing has been under-researched, particularly in terms of basic, foundational numerical skills. However, research into the cognitive implications of ageing is vital in understanding differences between normal and pathological ageing, and in determining whether interventions may slow cognitive decline (Dixon, Bäckman, & Nilsson, 2004; Salthouse, 2009).

3.2.1 Foundational numerical abilities

There are two forms of basic numerical processing: non-symbolic (quantities, such as sets of dots) and symbolic (numerical symbols, such as Arabic digits). Foundational non-symbolic numerical skills, or the Approximate Number System (ANS: Halberda, Mazzocco, & Feigenson, 2008), obeys Weber's law, as indicated by size and distance effects (e.g. Dehaene, 1999; Piazza & Izard, 2009; Roitman et al., 2012). ANS acuity is demonstrated to improve in typical development, reflected by a decrease in the Weber fraction (w), with an average w in educated numerate adults of ~ 0.15 (Dehaene, 2009; Halberda & Feigenson, 2008; Halberda et al., 2008; Lipton & Spelke, 2004; Piazza et al., 2013). The ANS is suggested to serve as a foundation for the acquisition of a symbolic exact number system (ENS: Castronovo & Göbel, 2012; Dehaene, 2009; Verguts & Fias, 2004), acquired later in development through formal symbolic education (e.g. learning Arabic digits). The ENS facilitates automatic access between symbols attributed to numerosities and their corresponding magnitude (Dehaene, 2009; Verguts & Fias, 2004). Both non-symbolic and symbolic foundational numerical abilities have primarily been studied in children and young adults. Therefore, the impact of healthy ageing on these two basic numerical systems is not well known. Further investigation of this issue is of clear importance, notably considering evidence of cortical decline in the parietal lobes in healthy ageing (for a review see Dennis & Cabeza, 2008), regions crucial to foundational numerical cognition (Cappelletti et al., 2010; Piazza & Izard, 2009; Sasanguie et al., 2013). It is unclear whether such neurological changes manifest behaviourally in ageing, affecting older adults' foundational numerical abilities.

3.2.2 Numerical cognition in ageing

Research on numerical cognition in ageing has mostly focused on exact, complex abilities such as arithmetical problem solving (e.g. Duverne & Lemaire, 2004; Lemaire & Arnaud, 2008). These early studies have forwarded contradictory conclusions, with some finding an age-related decline in arithmetic problem solving (Duverne & Lemaire, 2004), and poorer efficiency in choosing appropriate strategies (Duverne & Lemaire, 2004; Lemaire & Arnaud, 2008; El Yagoubi et al., 2005). However, some age-related declines during numerosity tasks have been attributed to reduced processing speed in ageing, rather than decreased numerical abilities specifically (Salthouse & Kersten, 1993). Moreover, others have found no impact of ageing or even superior symbolic skills in older adults (Cappelletti et al., 2014; Salthouse & Kersten, 1993). A limited number of studies have investigated non-symbolic numerical processing in ageing, with similar contradictory results: some suggest deteriorated basic non-symbolic numerical processing in ageing (Trick et al., 1996), including slower quantity estimation (Gandini et al., 2009; Geary & Lin, 1998; Li et al., 2010), whilst others found preserved non-symbolic (when distracters were absent: Watson et al., 2005) and continuous quantity skills in older age (Lambrechts et al., 2013).

3.2.3 Foundational numerical abilities in ageing

In Halberda et al.'s (2012) large online study of the ANS across the life-span, ANS acuity was concluded to decline from around age 30. However, no further discussion of this age-related decline was undertaken by the authors. Further, closer scrutiny of the data suggests higher individual variability for the older participants, and smaller participant numbers for the older age groups compared to the younger groups. Cappelletti et al. (2014) presented the first study to directly investigate the impact of ageing on foundational numerical abilities, comparing older and younger participants' performances on a non-symbolic quantity discrimination task. The authors initially found poorer precision of numerosity representation (larger *w*) in the older group compared to the younger group. Although such results suggest declined ANS acuity in older age (as in Halberda et al., 2012), further analyses found that older adults only performed more poorly than younger adults on trials requiring the inhibition of perceptual information incongruent with numerosity (fewer but larger dots). The authors therefore concluded that apparently poorer ANS acuity in ageing may be accounted for by impaired inhibitory skills (Hasher & Zacks, 1988) rather than reduced precision of numerical representations. Further, the effect of ageing on foundational symbolic numerical abilities was not directly discussed, and has so far only been investigated with the use of smaller numerical ranges (1-9: Cappelletti et al., 2014; Geary & Lin, 1998).

3.2.4 The current study

Although the impact of ageing on foundational numerical skills has recently begun to be investigated, it remains unclear whether such abilities decline in ageing. This question is still very much open in terms of basic symbolic and non-symbolic numerical skills. In all age populations, clear measures of ANS acuity have been used infrequently, which has potentially contributed to inconsistent results found in the literature (Gilmore, Attridge, & Inglis, 2011; Price, Palmer, Battista, & Ansari, 2012; Szűcs et al., 2013). In addition, direct investigation of basic symbolic abilities in ageing has been largely ignored. The current study aims to measure the number sense, both non-symbolic (ANS) and symbolic (ENS) foundational skills in younger and older adults, whilst controlling for mathematical achievement, general cognitive ability and years of education to establish whether basic numerical skills decline in ageing (Duverne & Lemaire, 2004; Gandini et al., 2008; Halberda et al., 2012; Lemaire & Arnaud, 2008; Li et al., 2010), or remain stable (Cappelletti et al., 2014; Dormal et al., 2012; Lambrechts et al., 2013; Lemaire & Lecacheur, 2007). Firstly, ANS acuity will be assessed using the non-symbolic numerical discrimination task Panamath, which has been standardised across thousands of participants (Halberda et al., 2012), and represents a similar paradigm to that used recently in the literature on ANS acuity in ageing (Cappelletti et al., 2014, 2015). In investigating non-symbolic numerical abilities in ageing, a variety of relatively long presentation times may have encouraged counting (e.g. Gandini et al., 2008; Lemaire & Lecacheur, 2007). Further, in some studies the effect of perceptual variables such as size and cumulative area of stimuli on numerosity judgements were not accounted for (e.g. Gandini et al., 2008). Finally, where Halberda et al. (2012) found declined ANS acuity in ageing, the impact of incongruent trials requiring inhibitory control were not directly investigated, making a comparison between their findings and those of Cappelletti et al. (2014) difficult. The current chapter addresses such concerns to achieve a clearer understanding of the impact of ageing on foundational non-symbolic numerical skills. This aim was addressed by: a) using a short presentation time (200ms) for non-symbolic discrimination to clearly measure numerosity discrimination acuity, rather than counting; b) controlling dot size and total cumulative area with the introduction of congruent and incongruent trials, allowing for further dissociation between possibly impaired numerosity skills and declined inhibitory control in ageing (Cappelletti et al., 2014); and c) using three measures of ANS acuity (accuracy, RTs and *w*) to assess the global impact of ageing on foundational non-symbolic abilities (Halberda et al., 2008). Secondly, the current chapter seeks to investigate whether ageing, with its inevitable increase in life-long exposure to numbers, is associated with refined or impaired foundational *symbolic* numerical abilities. As the effect of ageing on foundational symbolic numerical skills has yet to be directly studied, basic symbolic numerical skills were investigated with a comparison task using simultaneously presented pairs of two-digit Arabic numbers (Nuerk et al., 2001).

3.3 Method

3.3.1 Participants

Participants for all studies reported within the thesis consisted of both younger (18-25) and older adults (60+). Younger adults were recruited through the Psychology Department at the University of Hull, and were mostly Undergraduate students receiving course credit for participation, or Postgraduate students volunteering without incentive. Older participants were recruited from the community using posters and community outreach. A total of 156 older adults were recruited during the PhD. In each chapter, the number of participants taking part and the number excluded from the analyses is stated. All participants included within the studies confirmed normal or corrected vision, along with no history of severe clinical depression or any other psychiatric disorder. Participants were first-language English, due to the use of an English spelling task to assess general cognitive ability. All research reported within the thesis received ethical approval from the University Of Hull Department Of Psychology Ethics Committee. Participants provided written informed consent prior to participation. Testing took between 1 and 2 hours per participant for each study.

For the current study, 52 participants were recruited; 26 older adults aged 60 - 77 (14 males; M = 65, SD = 4.5) and 26 younger adults aged 19 - 25 (6 males, M = 20.5, SD = 1.7). Two participants' data (one from each group) were not included in the final analyses due to a computer error. As a result, a total of 50 participants' data were analysed (25 per age group). Amongst the younger group, 20 undergraduate students received course credit for participation.

3.3.2 Materials and procedure

Firstly, a series of control measures were used. The Mini Mental State Exam (MMSE: Folstein, Folstein, & McHugh, 1975 as in Dormal et al., 2012; Gandini et al., 2009) was administered to the older group, and the Geriatric Depression Scale (GDS: Yesavage et al., 1982) to all participants to rule out cognitive impairment and depression (depressed older adults are more likely to display cognitive changes than younger adults: Fiske, Wetherell, & Gatz, 2009). All older participants presented healthy MMSE scores over 27. Three participants from the older group presented a borderline score of 5 on GDS, and one participant from the younger group a score of 8, which could indicate depression. Their data were not excluded, as in comparing their performance (i.e. symbolic and non-symbolic RTs, accuracy and non-symbolic *w*) to the remainder of the group using a modified *t*-test (Crawford & Garthwaite, 2002), their results did not significantly differ (p_s >.1). The spelling subtest of the Wide Range Achievement Test 4 part 2 (WRAT4: Wilkinson & Robertson, 2006) was used to control for general cognitive abilities (e.g. Castronovo & Göbel, 2012; Sasanguie et al., 2013). Forty two words increasing in difficulty were read out and presented within a sentence, with participants writing their answers. As in Castronovo and Göbel (2012), a calculation task based on the Graded Difficulty Arithmetic Test (Jackson & Warrington, 1986), was used to measure participants' mathematical achievement (overall percentage correct). This timed paper and pen task consisted of three sections, comprised of one easy and one difficult subsection each: additions and subtractions included a 30 second (s) (easy) sub-section and a 90s (difficult) sub-section, and multiplications included a 40s and 4 minute sub-section. Questions were presented and answered in written Arabic format. Participants answered as many questions as possible.

Second, two computerised tasks were applied to investigate basic non-symbolic and symbolic numerical skills. Panamath was used to measure non-symbolic numerical abilities and ANS acuity (Halberda et al., 2008). Participants judge which of a set of yellow and a set of blue dots is more numerous. To measure basic symbolic numerical abilities, a classic symbolic comparison task was used. In this task, participants decide which of two two-digit Arabic numbers is the largest (in magnitude: Nuerk et al., 2001). Unless otherwise stated, all computerised tasks reported in the thesis were conducted on an AMD Athlon computer (1280x1024 res), with participants sitting 50cm away from the screen and responding using the keyboard.

Each participant took part in a single testing session split into two counterbalanced phases. In the first phase, participants undertook the MMSE, GDS and WRAT 4 spelling task, as well as the non-symbolic comparison task. In the second phase, participants undertook the calculation task and the symbolic comparison task.

3.3.3 Non-symbolic comparison task

Stimuli were a set of blue and a set of yellow dots simultaneously presented for 200ms (as in Halberda et al., 2012). The study utilised the Panamath software for researchers (www.panamath.org: Halberda et al., 2008). Fast stimulus presentation was used (as in Cappelletti et al., 2014; Halberda et al., 2008) to reduce the likelihood of counting and the influence of working memory, increasing the reliability of directly testing the ANS (Maylor, Sheehan, Watson, & Henderson, 2008). Participants decided whether the blue or yellow dots were more numerous by pressing either ‘A’ or ‘L’ on the keyboard, which were covered with blue and yellow circles respectively. The yellow dots always appeared on the left of the screen, and the blue dots on the right. Total cumulative area of each dot array was adapted to control for the influence of perceptual variables. In half the trials, the size of the average blue dot was equal to that of the average yellow dot. Therefore, the more numerous set also had a larger total area (congruent trials). For the other half of the trials, the number of blue pixels and yellow pixels was equal regardless of numerosity (incongruent trials: Halberda et al., 2008). Average dot size was therefore necessarily smaller in the more numerous set. Participants were asked to avoid counting and answer approximately. Each trial started with the participant pressing the space bar. Dot stimuli were then presented (200ms), immediately followed by a colour-matched backward mask (200ms). A prompt then remained on-screen until an answer was provided. In half of the trials, the blue dots were more numerous, and in the other half the yellow dots were more numerous. Accuracy, RTs and the Weber fraction (*w*) were measured. Two trials were first used as practice trials, data from which were not included in the final analyses. In total there were 384 experimental trials, split into four ratio bins, as in Halberda and Feigenson (2008): Bin 1 = ratio 1.2; Bin 2 = ratio 1.3; Bin 3 = ratio 1.8; and Bin 4 = ratio 3. Ratio bins denote the ratio between the number of blue and yellow dots (ratio= bigger set/smaller set). For example, stimuli were categorized as being in Bin 1 (ratio 1.2) when 11 yellow dots and 13 blue dots were presented (13/11 = 1.2). According to Weber’s law, as the ratio increases, task difficulty decreases (Halberda et al., 2008). Dot numerosities ranged from 5 to 21 for each coloured set. Analyses will investigate the effect of ratio and age group on ANS acuity (accuracy, RTs, and *w*). Throughout the thesis, Weber fractions for each participant’s performance on the non-symbolic comparison task were calculated using the automated Excel scripts provided on the Panamath resources website:

(http://panamath.org/wiki/index.php?title=Tutorial_3:_How_to_Determine_w_Using_Our_Automated_Scripts). Inputting each participant's data and running the scripts in Excel generated a Weber fraction alongside other ANS acuity outcomes (accuracy and RTs at each ratio bin). Although this automated script utilises a default Jolicouer outlier removing technique, the command for this outlier removal method was removed so that a consistent outlier-removing method is used throughout the thesis (trials with RTs 3*SDs lower or higher than each participant's mean RT are trimmed). After trimming, accuracy scores for each participant at each ratio bin were used to model the *w*. The model for fitting the *w* to each participant's data replicated that described in Full Methods by Halberda et al. (2008): "Percentage correct was modelled as a function of increasing ratio (larger set/smaller set, or n_2/n_1). The numerosity for the blue set and yellow set were represented as Gaussian random variables (that is, X2 and X1) with means n_2 and n_1 and standard deviations equal to the Weber fraction $w*n$. Subtracting the Gaussian for the smaller set from the larger set returned a new Gaussian with a mean of $n_2 - n_1$ and a standard deviation of $w\sqrt{(n_1^2 + n_2^2)}$ (simply the difference of two Gaussian random variables). Percentage correct was then equal to 1 - error rate, in which error rate is defined as the area under the tail of the resulting Gaussian curve, computed as:"

$$\frac{1}{2}\operatorname{erfc}\left(\frac{n_1 - n_2}{\sqrt{2}w\sqrt{n_1^2 + n_2^2}}\right)$$

Therefore, percentage correct on the non-symbolic comparison task is fitted as a function of the Gaussian approximate representations for the two sets (i.e. the blue and yellow arrays), resulting in an overall *w*. A participant's *w* represents the standard deviations for the Gaussian representations of the ANS, therefore representing the amount of overlap between any two Gaussian numerical representations (Halberda et al., 2008), otherwise described as the amount of 'noise' present within an individual's approximate numerical representations.

3.3.4 Symbolic comparison task

The symbolic comparison task was similar to that of Nuerk et al. (2001)[i]. Stimuli comprised of a pair of two-digit numbers (e.g. 46 and 58), presented simultaneously (horizontally), in black font on a white background. Stimuli pairs were grouped into four distance bins indicating the total numerical distance between the pair: Bin 1 = distances 6- 15; Bin 2 =

distances 16- 24; Bin 3 = distances 25- 49; Bin 4 = distances 51- 71. Task difficulty decreases with increasing distance bin. For example, the pair 31-81 has a larger global distance (distance of 50, Bin 4) than 31-51 (distance of 20, Bin 2), and is therefore an easier trial. Stimuli ranged from 21 to 98. Further, the compatibility of the digit pairs was manipulated. In half the trials pairs were ‘compatible’: the unit in the larger digit was always larger than its decade (e.g. 57), and the unit in the smaller digit was always smaller than its decade (e.g. 32). The other half were incompatible (e.g. 37 and 52). Finally, each of the four digits displayed on screen in any given trial were numerically different. Participants decided whether the larger number was on the left or right of the screen, responding as quickly as possible without sacrificing accuracy using the keyboard (A= left, L= right). There were 16 practice trials with feedback, followed by 240 experimental trials without feedback, split into two blocks. A black fixation cross appeared on a white background (1000ms), followed by the stimuli until response (up to 3000ms). Accuracy and RTs were recorded. The use of two-digit stimuli involves refined symbolic abilities, avoiding likely ceiling effects found in adults and older children when using single-digit stimuli (Lonnemann et al., 2011). The use of a larger numerical range should therefore allow greater discrimination between participants’ skills than in previous studies using a smaller numerical range (e.g. Cappelletti et al., 2014; Geary & Lin, 1998). Analyses will investigate the effect of distance and age group on accuracy and RTs.

3.4 Results

Group differences for control measures (GDS, Calculation task and Spelling task) and w_s were investigated using independent *t*-tests. ANOVAs were conducted on RTs and accuracy to assess the impact of ageing on non-symbolic and symbolic numerical skills, with ratio/distance bin as a within-subjects factor and age group as a between-subjects factor. Additionally, in the non-symbolic comparison task, ANOVAs were conducted for each age group to determine the effect of trial type (congruent or incongruent) on RTs and accuracy. Where sphericity was violated, Greenhouse-Geisser corrections apply. Ratio effects for each participant were further analysed by calculating individual regression slopes. Correlational analyses were conducted to determine whether mathematical achievement was related to basic symbolic and non-symbolic numerical skills. Finally, linear regressions further analyse the effect of age, education and control measures on symbolic and non-symbolic skills.

3.4.1 Control measures

In the calculation task, positive correlations ($p_s < .001$) were found between scores on the three sections (addition, subtraction, multiplication). For all participants, Mathematical Achievement (MA) was determined by calculating the total percentage correct of all three sections. Independent-samples *t*-tests indicated that older adults (M = 90.55%, SD= 6.90) presented significantly higher MA scores than younger adults (M = 68.23%, SD= 15.38; $t(33.3) = -6.62$, $p < .001$). In the spelling task, older adults (M = 86.19%, SD= 8.59) also scored significantly higher than younger adults (M = 78.67%, SD = 5.97; $t(48) = -3.60$, $p < .01$). There were no significant differences between groups on the GDS ($p > .2$), and years of education were similar between groups, $p > .6$ (older adults: M = 16.5 years, SD = 2.6; younger adults: M = 16.2 years, SD = 1.7). Overall, these results indicate that although both groups present similar levels of education, older people clearly demonstrate greater mathematical achievement. The results reflect previous findings indicating greater mathematical abilities in older adults (Cappelletti et al., 2014), with superior spelling ability in ageing also consistent with increased verbal knowledge across the lifespan (see Cappelletti et al., 2014 for vocabulary scores; Hedden & Gabrieli, 2004; Watson et al., 2005).

3.4.2 Non-symbolic comparison task

In the non-symbolic comparison task, ANS acuity was measured by accuracy, RTs, and *w* (Halberda et al., 2008). ANOVAs were conducted to assess the impact of age and ratio on RTs and accuracy. Further analyses were carried out to investigate the effect of ageing on performance on congruent and incongruent trials (Cappelletti et al., 2014). Data were trimmed by applying a 3 SD cut-off for RTs on correct responses (2.11% of data removed). Preliminary analyses indicated that neither group showed a speed-accuracy trade-off (older adults $r = .18$, $p > .38$; younger adults $r = .34$, $p = .1$). First, an independent-samples *t*-test indicated that there was no significant difference in *w* between age groups: $t(48) = 0.146$, $p = .88$. In both groups, the average *w* was .18, (older group SD = .182; younger group SD = .184), reflecting a similar *w* to previous literature (Piazza et al., 2004).

3.4.3 RTs

To determine the effect of age and ratio on RTs, a 4 (ratio bin) x 2 (age group) mixed ANOVA was conducted, with ratio bin as a within-subjects factor, and age group as a between-subjects factor. Ratio bin had a main effect on RTs, $F(1.52, 72.97) = 156.62$, $p < .001$. This reflects the classic ratio effect: the larger the ratio, the faster the response (Piazza & Izard, 2009). There was no main effect of age group on RTs, as both groups presented similar RTs, $F(1, 48) = .784$, $p > .3$ (younger group M = 874ms, SD = 308, older group M = 923ms, SD = 360). However, the ratio bin x age group interaction was significant, $F(1.52, 72.97) = 7.21$, $p < .01$ (see Figure 5). To further investigate this interaction, we computed each participant's linear regression slope for RTs, with ratio bin as a predictor (Castronovo & Göbel, 2012; De Smedt et al., 2009). An independent *t*-test showed that the non-symbolic ratio effect was significantly more pronounced in the older group (Mean regression slope = -90.15, SD = 35.84) than the younger group (Mean regression slope = -58.70, SD = 38.85; $t(48) = 2.98$, $p < .01$).

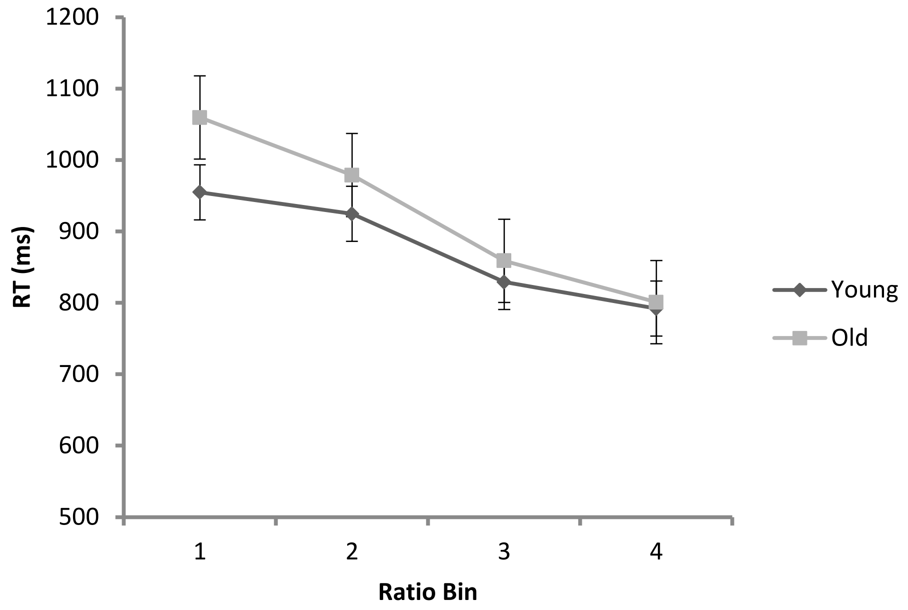

Figure 5: The ratio effect on younger and older adults' reaction times (RTs) in the non-symbolic numerical comparison task

3.4.4 Accuracy

A 4 (ratio bin) x 2 (age group) ANOVA investigated ratio and age effects on non-symbolic accuracy. There was a main effect of ratio bin, $F(1.96, 93.94) = 474.2$, $p < .001$, reflecting improving accuracy with increasing ratio (Bin 1 M = 74.59%, SD = 7.04, Bin 2 M = 84.62%, SD = 5.61, Bin 3 M = 98.50%, SD = 2.00, Bin 4 M = 99.52%, SD = 1.31: Piazza & Izard, 2009). There was no main effect of age group ($p > .7$), with both groups presenting similar accuracy (older group M = 89.57%, SD = 3.31, younger group M = 89.33%, SD = 2.97). The ratio bin x age group interaction was significant ($F(1.96, 93.94) = 3.57$, $p < .05$). To further investigate this interaction, regression slopes were calculated for each participant, with ratio bin as a predictor of accuracy. An independent *t*-test showed that there was no significant difference between the groups' regression slopes ($p > .2$). This indicates that the interaction cannot be accounted for by a global difference between the groups' ratio effect on accuracy. Independent *t*-tests also showed that accuracy scores were similar in both groups for each ratio bin ($p_s > .1$). Therefore, this interaction seems to be due to opposite patterns between the groups' processing of ratio bins 1 and 2, with the younger group presenting slightly greater accuracy than the older group in ratio bin 1 (M = 75.80%, SD = 6.06 in younger group; M = 73.38%, SD = 7.83 in older group), whilst the reverse can be found in bin 2 (M = 83.31%, SD = 4.78 in younger group; M = 85.93%, SD = 6.16 in the older group: see Figure 6).

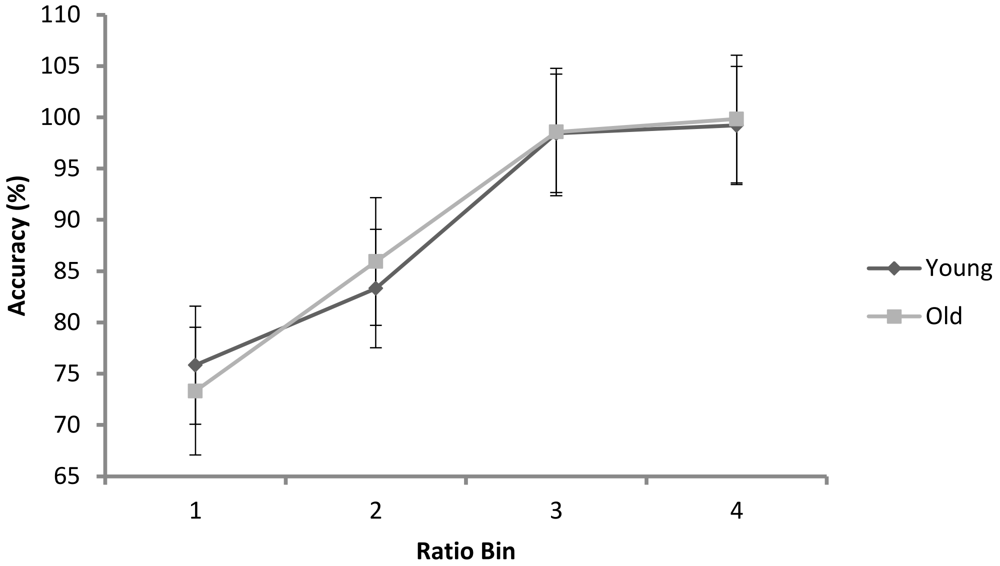

Figure 6: The ratio effect on younger and older adults' accuracy scores (%) in the non-symbolic numerical comparison task

Correlational analyses were conducted between mathematical achievement (MA) and non-symbolic acuity (*w,* RTs, and accuracy). Correlations between *w* and MA ($p > .2$) and *w* and non-symbolic RTs ($p > .1$) did not reach significance. Hierarchical regression analyses were conducted on RTs, accuracy, and *w* to investigate whether an effect of ageing on non-symbolic ANS acuity appears after controlling for possibly confounding variables (education, spelling and MA). Four steps were sequentially included in the analyses: 1) Education (years); 2) Spelling score; 3) MA; 4) Age Group; 5) Gender. All factors were non-significant predictors of RTs, accuracy, and *w* ($p_s > .1$).

These first results appear to show that non-symbolic foundational numerical skills are preserved in healthy ageing. However, since recent data has suggested impaired numerosity discrimination in older participants when inhibition skills are required (i.e. in incongruent trials: Cappelletti et al., 2014), we conducted further analyses. To investigate possible decline in non-symbolic numerical skills in ageing when inhibitory processes are required (Cappelletti et al., 2014), we ran a mixed ANOVA, with condition (congruent / incongruent) as a within-subjects variable and age group as a between-subjects variable on non-symbolic RTs, accuracy and *w*. In line with Cappelletti et al. (2014), we found a main effect of condition on *w,* with incongruent trials resulting in reduced ANS acuity (higher mean w = .20, SD = .06), compared to congruent trials (w = .16, SD = .04; $F(1,48) = 39.34$, $p < .001$). However, our results indicated that this congruency effect was similar for both age groups ($p > .7$), with no interaction ($p > .6$). For RTs, there were no main effects of condition (congruent trials mean RT = 897ms, SD = 199, incongruent = 901ms, SD = 200: $p > .2$) or age group ($p > .3$: mean RT older group = 923ms, SD = 360, younger group M = 874ms, SD = 309). Nevertheless, the condition x group interaction on RTs was marginally significant (p = .065), due to older adults' slightly slower RTs during incongruent trials (mean RT = 929ms, SD = 202) compared to congruent trials (mean RT = 919ms, SD = 200; $t(24) = -2.22$, $p < .05$), whereas younger participants presented similar RTs in both conditions ($p > .6$). Participants were more accurate during congruent trials (M = 91%, SD = 3.12) than during incongruent trials (M = 87%, SD = 3.91; $F(1,48) = 47.28$, $p < .001$). There was however no main effect of age group ($p > .7$), and no interaction ($p > .2$). Our results indicate that non-symbolic performance declined for incongruent trials compared to congruent trials in terms of w and accuracy regardless of age group. However, in line with Cappelletti et al.'s (2014) results, healthy ageing tends to be associated with a somewhat more pronounced decline in numerosity discrimination skills where inhibition is required, since the older group were slower during incongruent than congruent trials, with younger adults showing no such effect.

3.4.5 Symbolic comparison task

In order to investigate the impact of ageing on basic symbolic numerical skills, analyses were conducted on RTs and accuracy. RT data were trimmed by applying the same 3 SD cut-off as in the non-symbolic task (1.45% data removed). Neither group presented a speed-accuracy trade off (older adults: r = .25, $p > .2$; younger adults: r = .36, p = .1).

3.4.6 RTs

Distance and age group effects were investigated using a 4 (distance bin) x 2 (age group) mixed ANOVA. Distance had a main effect on RTs: the larger the distance, the faster the response, as explained by Weber's law, $F(2.09, 100.13) = 290.23$, $p < .001$ (Piazza & Izard, 2009). Younger adults were significantly faster (M = 613ms, SD = 72) than older adults (M = 768ms, SD = 94; $F(1, 48) = 44.97$, $p < .001$). A distance bin x age group interaction ($F(2.09, 100.13) = 12.94$, $p < .001$) appears to be mainly due to younger participants' similar RTs for distance bins 1 and 2 (mean RT = 645ms, SD = 79; mean RT = 648ms, SD = 78 respectively; p

> .6). On the contrary, older participants' RTs differed across all distance bins, including bins 1 and 2, illustrated by slower RTs in distance bin 1 (mean RT = 831ms, SD = 104), than distance bin 2 (mean RT = 802ms, SD = 95; F (1,24) = 22.34, p < .001, see Figure 7).

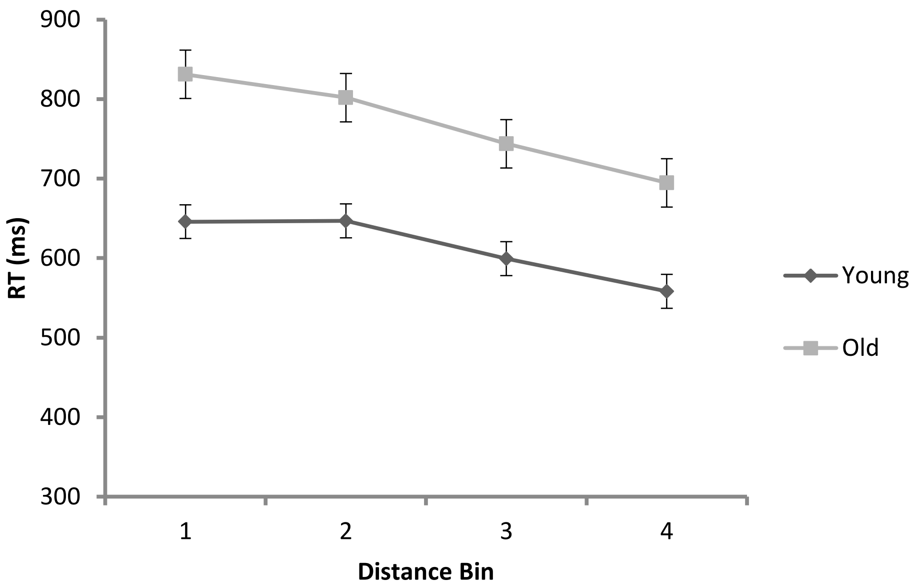

Figure 7: The distance effect on younger and older adults' reaction times (RTs) in the symbolic numerical comparison task

3.4.7 Accuracy

Similar analyses of accuracy show a main effect of distance in accordance with Weber's law, F(2.13, 102.25) = 53.46, p < .001: as global distance increases, so does accuracy (mean accuracy Bin 1 = 93.57, SD = 6.01, Bin 2 = 95.10, SD = 4.24, Bin 3 = 98.29, SD = 2.48, Bin 4 = 99.66, SD = 0.78: Piazza & Izard, 2009). There was also a main effect of age group, as older adults (M = 99%; SD = 2) were significantly more accurate than younger adults (M = 95%; SD = 3; F(1, 48) = 62.48, p < .001). The interaction between distance and age group was significant, F(2.13, 102.25) = 19.36, p < .001 (see Figure 8). Individual regression slope analyses illustrate that the symbolic distance effect on accuracy was significantly more pronounced in the younger group (mean regression slope = 3.44) than the older group (mean regression slope = 0.85; t(48) = 6.46, p < .001).

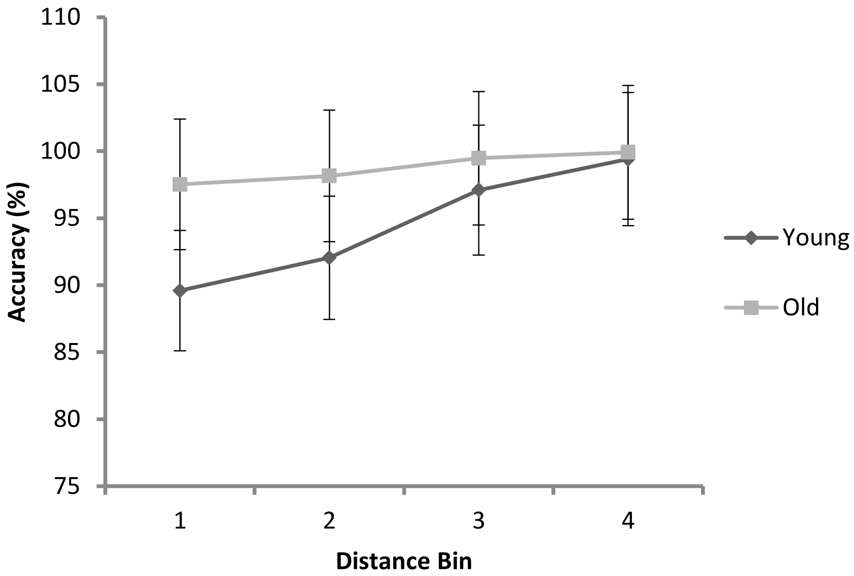

Figure 8: The distance effect on younger and older adults' accuracy (%) in the symbolic numerical comparison task

As in the non-symbolic task, correlational analyses were conducted between mathematical achievement (MA) and symbolic RTs and accuracy. Correlations between MA and symbolic RTs (r = .32, p < .05) and accuracy (r = .63, p < .001) were significant. Further, hierarchical regression analyses were conducted on RTs and accuracy to determine the effect of age group on symbolic processing when controlling for education, spelling, MA, and gender. Education, spelling scores and gender were non-significant predictors of symbolic performance (p_s > .3). Both MA and age group significantly predicted symbolic RTs (*Beta* = -.38, p < .05, *Beta* = .90, p < .001 respectively). Age strongly predicted RTs, accounting for 42% of the variance, $\Delta F(1, 45)$ = 41.73, p < .001. Crucially, being in the older group was the only significant predictor of higher accuracy (*Beta* = .60, p < .001). On all measures, age group accounted for a significant additional percentage of variance, $\Delta F(1, 45)$ = 20.91, p < .001), particularly for accuracy (19%). Overall, age affected symbolic comparison abilities over and above any other factor, most notably MA.

3.5 Discussion

The impact of healthy ageing on basic numerical abilities has only recently begun to be researched. In the field of numerical cognition, much attention has been paid to the number sense in children, and its link with mathematical achievement (De Smedt et al., 2009; Halberda et al., 2008; Libertus, Feigenson, & Halberda, 2013; Libertus, Odic, & Halberda, 2012; Piazza et al., 2013). Where investigation has turned to ageing, studies have mostly focused on higher-level numerical skills (e.g. Duverne & Lemaire, 2004; Lemaire & Arnaud, 2008). Those researching non-symbolic abilities find contradictory results, present methodological limitations (e.g. variable presentation times of stimuli, little or no control of perceptual variables), and tend to focus on a single measure of ANS acuity, such as *w*. Some studies have found deteriorated non-symbolic numerical abilities with age (Halberda et al., 2012), whereas others have found no such effect once age-related inhibitory decline was accounted for (Cappelletti et al., 2014). In terms of basic symbolic abilities, findings are sparse and methods limited, with a focus on high-level arithmetical skills or the use of small numerical ranges in comparison tasks. Some studies suggested a decline in symbolic numerical processing in ageing (e.g. Duverne & Lemaire, 2004; Geary & Lin, 1998; Lemaire & Arnaud, 2008), whereas others support preserved (but potentially slower) symbolic abilities in older adults (Cappelletti et al., 2014; Salthouse & Kersten, 1993). More importantly, ageing and *basic* symbolic numerical skills have yet to be directly investigated. The current study addresses these issues in being the first to study both non-symbolic and symbolic numerical skills as foundational numerical skills in ageing. Our findings suggest that ageing does not have a detrimental effect on basic non-symbolic numerical processing, whilst it seems to have a positive effect on basic symbolic numerical processing and mathematical achievement. Additionally, our results further support previous research showing a positive effect of ageing on verbal knowledge (Cappelletti et al., 2014; Geary & Lin, 1998; Hedden & Gabrieli, 2004), as older age was associated with superior spelling performance.

The current findings on ageing and foundational non-symbolic numerical skills support recent research suggesting that healthy ageing is associated with the preservation of non-symbolic quantity processing (both continuous; Dormal et al., 2012; Lambrechts et al., 2013; and discrete; Cappelletti et al., 2014; Lemaire & Lecacheur, 2007), as non-symbolic discrimination skills were preserved in the older group. These results are in line with the suggestion that basic numerical skills may be resilient to cognitive ageing as they stem from a primitive, innate system originating from evolutionary abilities (Feigenson et al., 2004; Lambrechts et al., 2013). Previous contradictory results suggesting a decline of ANS acuity in ageing may stem from different methodological issues. For example, Halberda et al. (2012) concluded that ANS acuity decreases steadily from age 30. However, the study's older group shows a large variability in age range (45-85 years), which could be reflected in terms of a large variability in performance. Additionally, as highlighted by Cappelletti et al. (2014), no distinction was made by Halberda et al. (2012) between performances on congruent and incongruent trials. It is therefore unclear to what extent Halberda et al.'s (2012) finding of deteriorated ANS acuity in ageing may be attributable to poorer performance on incongruent trials due to reduced inhibitory control, or to deterioration in other functions such as visual acuity (Uittenhove & Lemaire, 2015).

Our results, in line with previous findings (Cappelletti et al., 2014, 2015; Li et al., 2010), support the idea that inhibition should be considered when assessing numerosity discrimination skills, particularly in older groups. Indeed, our data on trials involving inhibitory control indicate that all participants were affected when continuous perceptual variables were incongruent to numerosity, as both groups were less accurate, presenting larger mean w_s. These findings reflect previous research demonstrating the impact of continuous perceptual variables on numerosity judgements (Dakin, Tibber, Greenwood, Kingdom, & Morgan, 2011; Gebuis & Reynvoet, 2012a; Hurewitz, Gelman, & Schnitzer, 2006). Moreover, supporting the findings of Cappelletti et al. (2014), ageing appears to be associated with greater sensitivity to interference from incongruent continuous variables, as older participants were somewhat slower in incongruent trials than congruent trials, whilst younger participants presented similar RTs regardless of congruency. This pattern of response times in the older group may represent impaired inhibitory control of a response based on dot size in order to respond to numerosity (e.g. Cappelletti et al., 2014). Speculatively, that both younger and older participants in our study, rather than older participants alone as in Cappelletti et al. (2014), presented declined accuracy and higher *w* in incongruent trials may be accounted for by the use of a backward mask in the current study to eliminate short-term memory representations of stimuli. The absence of a backward mask in Cappelletti et al.'s (2014) study may have benefited younger participants, as they have stronger short-term memory abilities than older adults (Salthouse & Babcock, 1991), and therefore a superior 'after image' (Sperling, 1960) of stimuli. This may have resulted in better performance for the younger group during incongruent trials due to this group being more able to visually recall the stimuli, overcoming perceptual variable incongruency. Another methodological difference was that Cappelletti et al. (2014) used spatially intermixed dot displays, whereas separate arrays were used in the current study (as in Fuhs & McNeil, 2013; Gilmore et al., 2013; Smets, Gebuis, & Reynvoet, 2013). Recent research has suggested that differences in stimulus display methods may lead to unreliable ANS measures (Hurewitz et al., 2006; but see Price et al., 2012; Szűcs et al., 2013). Intermixed displays during a short presentation time could be more difficult for older participants due to their reduced useful field of view (Lemaire & Lecacheur, 2007), likely compounding poorer performance on the more difficult incongruent trials. Our results on incongruent trials are therefore somewhat in line with Cappelletti et al. (2014), supporting the hypothesis that previous findings of impaired numerosity discrimination in ageing may reflect inhibitory decline, rather than impoverished non-symbolic numerical processing as such. Overall, our findings on non-symbolic numerical abilities further support the conclusion that ageing does not affect basic non-symbolic numerical abilities, possibly as a result of the innate nature of the ANS (Feigenson et al., 2004; Lambrechts et al., 2013).

Secondly, our study highlights a positive impact of ageing on basic symbolic numerical skills, as well as mathematical achievement. With the introduction of a larger numerical range, we were able to directly study the effect of ageing on symbolic numerical skills, whilst avoiding likely ceiling effects of using single-digit stimuli (Lonnemann et al., 2011). Our data indicate that ageing appears to be associated with superior foundational symbolic numerical abilities. Although older participants presented slower RTs due to processing-speed decline (Salthouse, 1996), they were more accurate than younger participants, with a less pronounced symbolic distance effect on accuracy. These results extend Cappelletti et al.'s (2014) primary observations of preserved basic symbolic numerical abiltities in ageing on a smaller numerical range. Altogether, these findings suggest the presence of a better anchored and more precise symbolic numerical representation, as well as greater mathematical achievement in ageing, as a result of lifetime experience with numbers. The results are therefore in line with the suggestion that symbolic discrimination abilities improve with age (Cappelletti et al., 2014; De Smedt, Noël, Gilmore, & Ansari, 2013; Salthouse & Kersten, 1993), likely due to cumulatively increasing experience with numbers across the lifespan leading to advanced automaticity of numerical processes (e.g. counting: Uittenhove & Lemaire, 2015).

Symbolic and non-symbolic distance effects have been found to be affected by individual number knowledge, with mathematical achievement being negatively associated with the symbolic distance effect in children (e.g. De Smedt et al., 2009; Holloway & Ansari, 2009) and adults (e.g. Castronovo & Göbel, 2012), but positively correlated with the non-symbolic distance effect (in children Gilmore, McCarthy, & Spelke, 2010; and in adults, Castronovo & Göbel, 2012). Likewise, in the current study, participants in the older group presented greater mathematical achievement, as well as a decreased symbolic distance effect on accuracy and an increased non-symbolic distance effect on RTs compared to the younger group. The current results therefore give further support to the notion that longer lifetime exposure to numbers is associated with greater mathematical knowledge, as well as a better defined symbolic number system and a greater tendency to automatically transcode non-symbolic numerosities into their corresponding symbolic representations prior to processing (see Figure 9: Castronovo & Göbel, 2012; Gilmore et al., 2010; Halberda et al., 2008).

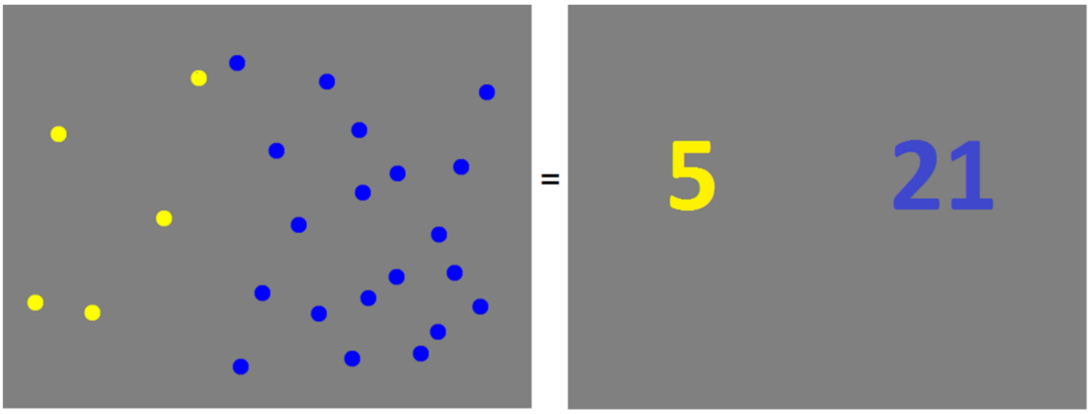

Figure 9: An illustration of the process of transcoding non-symbolic stimuli into their symbolic counterparts before proceeding to discriminate the largest numerosity

Further to our findings regarding the effect of ageing on basic non-symbolic and symbolic numerical abilities, the link between non-symbolic abilities and mathematical achievement was investigated, as it represents a key theme in numerical cognition research, particularly in early development. Non-symbolic acuity and mathematical achievement did not correlate in either age group, reflecting recent findings (Castronovo & Göbel, 2012; Inglis, Attridge, Batchelor, & Gilmore, 2011; Price et al., 2012; but see Libertus et al., 2012), reinforcing the hypothesis that ANS acuity may reach a maximum in adulthood, reducing the strength of a link between the ANS and mathematical ability in adults (Castronovo & Göbel, 2012). Alternatively, mathematical achievement may only correlate with symbolic abilities, both in children (Holloway & Ansari, 2008, 2009) and adults (Castronovo & Göbel, 2012), a prediction further supported by the current findings, as well as neuropsychological evidence of a relationship between specific brain regions used for both basic and advanced symbolic numerical processing (Ansari et al., 2006; Cantlon et al., 2006; Izard et al., 2008; Piazza et al., 2007). Recent evidence suggests a crucial role of efficient and automatic access to Arabic digit representations in adults' arithmetical abilities. Using matching paradigms with adult populations, Sasanguie and Reynvoet (2014) found that mathematical achievement scores were only related to performance on a task where aurally-presented numbers were matched with visually-presented Arabic digits. There was no relationship between adults' mathematical abilities and their performance on the same matching task when aurally-presented numbers were to be matched to dot patterns (i.e. non-symbolic quantities). Such results were concluded to imply that adults may not automatically access the non-symbolic representation of an Arabic digit, and therefore that a link between foundational symbolic acuity (e.g. symbolic comparison task performance) and mathematical achievement in adults may not be due to superior mapping between non-symbolic representations and their symbolic Arabic digit, but may be due to a relationship between superior mathematical ability and more efficient processing of the digit itself. These findings therefore support those of the current study in that a link between mathematical achievement and ANS acuity was not found, possibly as the non-symbolic representation of a symbolic number is not accessed by adults during mathematical processing. By directly investigating foundational non-symbolic and symbolic numerical skills in ageing, our study provides further evidence that the ANS corresponds to a primitive number system resilient to ageing, as well as being unrelated to education and increased practice with age (Castronovo & Göbel, 2012; Feigenson et al., 2004; Lambrechts et al., 2013). On the other hand, the ENS, similarly to other education-related abilities, such as spelling and vocabulary (Hedden & Gabrieli, 2004), benefits from life-long exposure and practice associated with ageing. Improved basic symbolic processing and mathematical ability in the older group may be suggested to reflect a generational, qualitative difference between younger and older adults' mathematical education (Geary & Lin, 1998). However, regression analyses in the current study suggest that this is unlikely, as increasing age accounted for significantly more variance in symbolic discrimination accuracy than mathematical achievement.

The current findings further address the impact of ageing on cognition in general (Hedden & Gabrieli, 2004), suggesting that foundational numerical processing may be one of a few cognitive skills along with verbal memory, implicit memory, and emotional processes to be preserved in healthy ageing. This chapter brings to light the effect of cognitive ageing on basic symbolic and non-symbolic numerical abilities. The current findings could additionally inform research into the effects of pathological ageing on numerical cognition, such as in Alzheimer's disease (AD) (Delazer, Karner, Proell, & Benke, 2006; Duverne, Lemaire, & Michel, 2003; Girelli, Vecchi, Annoni, & Luzzatti, 1999; Kaufmann et al., 2002; Khodarahimi & Rasti, 2011; Maylor, Watson, & Muller, 2005). As numerical cognition is largely dependent on the parietal lobes (Piazza & Izard, 2009; Roitman et al., 2012), and these regions of the brain undergo significant atrophy early in the course of AD (Bruner & Jacobs, 2013; Jacobs et al., 2011; Jacobs, Van Boxtel, Jolles, Verhey, & Uylings, 2012) compared to normal ageing (Dixon et al., 2004), basic numerical tasks could prove a useful diagnostic tool. Such application may be advantageous as the tasks used in the current study are straightforward to apply. Moreover, as the measures remain stable in healthy ageing, their use may provide a specific marker for AD. The discovery of differences in basic numerical skills between healthy older adults and those with AD could assist in the detection of the disease at the earliest stages, vital in developing more effective treatments and attaining better outcomes (Salthouse, 2009). In particular, the non-symbolic comparison task used in this study (Halberda et al., 2008) has been applied with populations of varying abilities, including very young children, demonstrating its flexibility of application and therefore the potential for use in clinical populations.

4 Chapter 3: Investigating enhanced symbolic numerical abilities in ageing: The case of priming effects

4.1 *Introduction*

4.1.1 *Contribution of the current chapter*

Chapter 2 found that foundational non-symbolic numerical abilities appear to be preserved in healthy ageing. Further, older adults demonstrated enhanced foundational symbolic numerical abilities compared to younger adults. Older adults achieved higher accuracy during symbolic comparison, with older age contributing to stronger foundational symbolic abilities over and above mathematical achievement, which was also higher in the older group. Furthermore, older adults showed a less pronounced distance effect on accuracy in comparing a pair of two-digit numbers than the younger group. The results suggest that symbolic numerical abilities may be enhanced across the lifespan due to cumulatively increasing exposure to symbolic numbers. Indeed, previous research has suggested that symbolic discrimination abilities improve with age (De Smedt et al., 2013), with lifetime experience using numbers facilitating enhanced symbolic numerical abilities with ageing (Defever et al., 2014; Holloway & Ansari, 2008; Reynvoet, De Smedt, & Van den Bussche, 2009). Such an effect may be due to a more refined symbolic numerical representation as a result of stronger links between non-symbolic and symbolic numerical representations across the lifespan. In a similar vein, previous research has demonstrated that the SNARC effect changes with age. The strength of the SNARC effect, whereby responses to smaller numbers are associated with the left hand, and responses to larger numbers with the right hand, increases across the lifespan and is at its strongest in older age (Hoffmann, Pigat, & Schiltz, 2014; Wood, Willmes, Nuerk, & Fischer, 2008). A cumulatively increasing strength of the SNARC effect may indicate a more embedded mental number line with increasing lifespan. Suggestions of better anchored numerical representations with increased numerical experience are supported by the interpretation of more pronounced non-symbolic distance effects on RTs for mathematicians and older adults (groups with superior mathematical experience and achievement), as a 'transcoding effect': participants with higher mathematical achievement seem to demonstrate a tendency to transcode non-symbolic stimuli into their symbolic form before processing (Castronovo & Göbel, 2012; as in chapter 2: Norris, McGeown, Guerrini, & Castronovo, 2015). The results from chapter 2 provide further support for this hypothesis, as older adults demonstrated a stronger non-symbolic ratio effect on RTs compared to the younger group, but not on accuracy. Stronger foundational symbolic numerical abilities have also been linked to higher mathematical achievement in the literature. The results from chapter 2 demonstrate that older adults presented higher mathematical achievement scores than younger adults, an advantage related to their stronger basic symbolic numerical discrimination abilities. Previous research supports these findings, in that a link between mathematical achievement and foundational numerical abilities has been found for both symbolic (e.g. De Smedt et al., 2013; Holloway & Ansari, 2009) and non-symbolic abilities (Halberda & Feigenson, 2008; Halberda et al., 2012; but see Castronovo & Göbel, 2012; Inglis et al., 2011). If ageing is associated with better anchored numerical representations on the mental number line (as evidenced by older adults' enhanced symbolic processing and stronger SNARC effects), further investigation of the nature of such age-related changes in symbolic numerical acuity is required. The current study therefore aims to further investigate the possible mechanisms behind enhanced foundational symbolic numerical abilities in ageing.

4.1.2 Investigation of foundational symbolic numerical abilities in ageing

In order to investigate foundational symbolic numerical abilities, most studies with participants aged across the lifespan have utilised magnitude comparison paradigms, whereby participants decide which side of the screen contains the larger number (e.g. 2 – 9: Cappelletti et al., 2014; Geary & Lin, 1998). Further, some researchers investigating numerical cognition more broadly in ageing have tested complex symbolic abilities such as arithmetical problem solving (e.g. Duverne & Lemaire, 2004; Lemaire & Arnaud, 2008). Conclusions regarding the impact of ageing on such procedural, exact abilities have been mixed. Some authors have concluded that exact symbolic abilities decline in ageing, due to reduced flexibility in choosing effective strategies (Duverne & Lemaire, 2004; Lemaire & Arnaud, 2008; El Yagoubi et al., 2005). On the other hand, some suggest preserved or even enhanced arithmetical and symbolic numerical abilities with ageing (Salthouse & Kersten, 1993, as found in chapter 2). Preservation of exact symbolic numerical abilities in older age, specifically in arithmetic and calculation, may be categorised alongside the preservation of other crystallised abilities (e.g. vocabulary: Christensen, 2001). On the contrary, some argue that differences between younger and older adults' symbolic numerical abilities may reflect generational, qualitative differences in mathematical education (Geary & Lin, 1998). Indeed, cohort effects, which are inherently difficult to avoid in ageing research, may complicate dissociation between an effect of ageing and a simple group difference (Hedden & Gabrieli, 2004). However, the findings from chapter 2 indicated that ageing, over and above calculation abilities and level of education, is associated with refined foundational symbolic numerical abilities, possibly as a result of lifetime experience using numbers. Comparable preservation of foundational symbolic numerical abilities was found by Cappelletti et al. (2014) using a single-digit symbolic comparison task. Such findings therefore suggest that the mental representation of symbolic number may become further strengthened and embedded across the lifespan and into older age, resulting in stronger symbolic numerical abilities in older adults. The current study will use a numerical priming paradigm to further investigate the possibility of a more refined mental representation of number in older compared to younger adults. Participants will be required to categorise a symbolic number as smaller than 5 or larger than 5 when the target is either interfered or facilitated by a congruent or incongruent symbolic number prime. The study will therefore serve to further investigate the nature of enhanced symbolic abilities in ageing found using a comparison task in chapter 2, with a priming task sensitive to the automatic activation of symbolic numerical representations.

4.1.3 Mental representation of symbolic number

Symbolic numbers are understood to activate a neuronal representation of a given number on a mental number line with a Gaussian-function, logarithmic or linear scale (Dehaene & Changeux, 1993; Dehaene, 1997). Debate surrounding whether internal numerical representations are logarithmic or linear has yet to be resolved (Dehaene, 2001, 2003). Although the logarithmic vs. linear debate continues, in both models each numerosity representation is tuned to an individual Gaussian curve on a mental number line, representation that spreads to and overlaps with nearby numbers. Therefore, when a target number is activated, numbers close to the target are also activated (e.g. 4 and 6 become somewhat activated when representing '5': Piazza et al., 2004), with such activations dissipating with distance (i.e., 3 and 7 may also become somewhat activated in this example, although to a lesser extent than the numbers closer to 5: Dehaene & Changeux, 1993; Dehaene, 1997; den Heyer & Briand, 1986). Such spreading activation models account for size and distance effects observed during numerical tasks. The distance effect refers to poorer discrimination of two numerosities when they are numerically close (e.g. 5 and 6 will be more difficult to discriminate than 5 and 9 due to their closer proximity on the mental number line: Dehaene, 1997; Moyer & Landauer, 1967). Further, representational overlap becomes larger with increasing numerosity, resulting in size effects (e.g. 4 and 7 will be easier to discriminate than 14 and 17, even with identical numerical distances: Dehaene & Changeux, 1993; Dehaene, 1997). Numerical comparison tasks (e.g. Moyer & Landauer, 1967) have most often been used in demonstrating classic distance and size effects, whereby participants are consistently demonstrated to show poorer performance in discriminating the larger of two quantities as the distance between them decreases, and as their magnitude increases. Number priming paradigms have additionally been utilised to further investigate the automatic nature of representational overlap on the mental number line, as such tasks generate the representation of a numerical prime which may facilitate or interfere with the proceeding representation of a target number.

4.1.4 Investigating numerical representations using number priming

Number priming studies evolved from similar paradigms initially investigating the effects of presenting word primes on the recognition of letter-string targets as words or non-words (e.g. Meyer & Schvaneveldt, 1971). Early studies presenting a prime either prior to or concurrent with a target found that participants' decisions in categorising a target as a word or non-word were affected by the presence of a congruent or incongruent prime (Meyer & Schvaneveldt, 1971). If the prime was incongruent (e.g. nonsense letter string prime, followed by a word target), responses to a target were slower and less accurate than when the prime was congruent (e.g. a word prime followed by a word target). Further, deciding whether a word belongs to a certain category is facilitated by primes belonging to the same category (e.g. prime- water, target- swim: Howard, Shaw, & Heisey, 1986). Meyer and Schvaneveldt (1971) suggested that 'spreading excitation' may explain quicker and more accurate responses in categorising more strongly 'related' words as either 'living things' or 'non-living things'. For example the prime 'TULIP' has a stronger facilitatory effect for the correct categorisation of the target 'DAISY' compared to 'ZEBRA', even though they both belong to the 'living things' category: "excitation" was suggested to spread more effectively between the more closely related prime-target pairs. This early theory mimics spreading activation theories of numerical representation on the mental number line, whereby numerosities close to the activated number are also activated in a Gaussian function (Dehaene, 1997).

Number priming studies evolved from early work on words and semantic categorisation discussed above. Such number priming tasks generally presented a prime for a short duration (a digit or a number-word between 1 and 9), followed by a target number from the same range. Participants were either asked to decide whether the target was larger or smaller than a fixed standard (e.g. 5), or to make a parity judgement (decide whether the number is odd or even). Parity judgement tasks are suggested to require participants to access numerical representation at a semantic level, ensuring that a deeper, conscious level of processing is achieved (i.e. the task cannot be completed by simply recognising number at a basic, perceptual level: Fias, Reynvoet, & Brysbaert, 2001). However both parity judgement and larger/smaller number priming tasks consistently find a numerical priming *distance* effect and a numerical priming *congruency* effect (henceforth priming effects: Defever et al., 2014; Dehaene et al., 1998; Fabre & Lemaire, 2005; Koechlin, Naccache, Block, & Dehaene, 1999; Ratinckx, Brysbaert, & Fias, 2005; Reynvoet & Brysbaert, 1999; Reynvoet, Brysbaert, & Fias, 2002; Reynvoet, Caessens, & Brysbaert, 2002; Reynvoet et al., 2009; Reynvoet, Ratinckx, & Notebaert, 2008; Van Opstal, Gevers, Moor, & Verguts, 2008). In numerical cognition, the priming *distance* effect refers to a faster and more accurate response when the prime is numerically close to the target (see Figure 11), and the priming *congruency* effect refers to a faster and more accurate response when both the prime and the target would illicit the same response (e.g. both are larger than 5, or both are even; see Figure 10). Numerical priming effects have also been demonstrated across-notation, i.e. tasks where a number word prime is presented ('TWO'), followed by an Arabic digit target ('3'), or vice versa (Dehaene et al., 1998; Fias et al., 2001; Reynvoet, et al., 2002; but see Koechlin et al., 1999; Reynvoet & Brysbaert, 2004), and when primes and targets are presented intra or interhemispherically (Reynvoet et al., 2008).

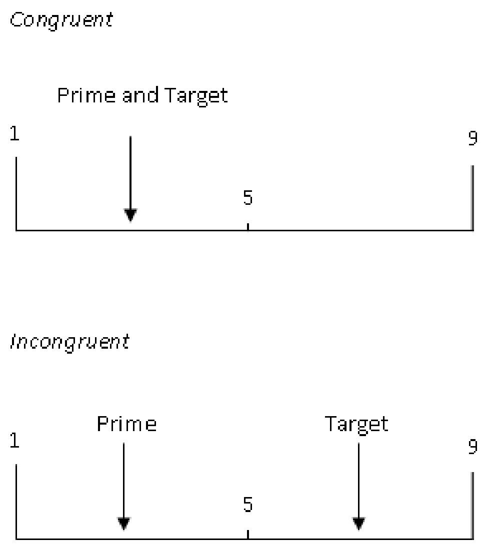

Figure 10: An illustration of the priming congruency effect. When the prime and target would both illicit the same response (smaller or larger than 5), the trial is congruent. However, where the prime activates a different response to the target, the trial is incongruent

It is suggested that the presence of numerical priming effects indicate that even unconsciously processed numerical stimuli are processed at a semantic level, as would be the case during conscious processing (Dehaene et al., 1998; Koechlin et al., 1999). This means that the prime, even when only presented very briefly, is attended to and then categorised with respect to task demands (e.g. smaller/larger or odd/even). The response prepared to the prime may either facilitate or interfere with a response to the target depending on trial congruency (Dehaene et al., 1998; Koechlin et al., 1999). For example, in a smaller/larger task, a prime of '2' is facilitatory to a target of '3' (i.e. they both elicit a 'smaller' answer: congruent trial), but interferes with a response to the target '8' (the prime elicits a 'smaller' answer, incongruent to the 'larger' answer to the target: Dehaene et al., 1998; Koechlin et al., 1999). It is suggested that a participant must inhibit a response to an incongruent prime (Dehaene et al., 1998). Further, due to the priming distance effect, a response to the target '9' would be slower and less accurate when preceded by the prime '6' than by the prime '8', in that the prime '8' would more strongly activate '9' as a nearby representation than the prime '6' (see Figure 11). That priming effects are observed across-notation provides evidence for semantic processing of even very briefly displayed and unconsciously perceived primes (Dehaene et al., 1998; Kunde et al., 2003). Although Kunde et al. (2003) failed to demonstrate consistent prime target distance effects, such effects have been replicated since (e.g. Van Opstal et al., 2008).

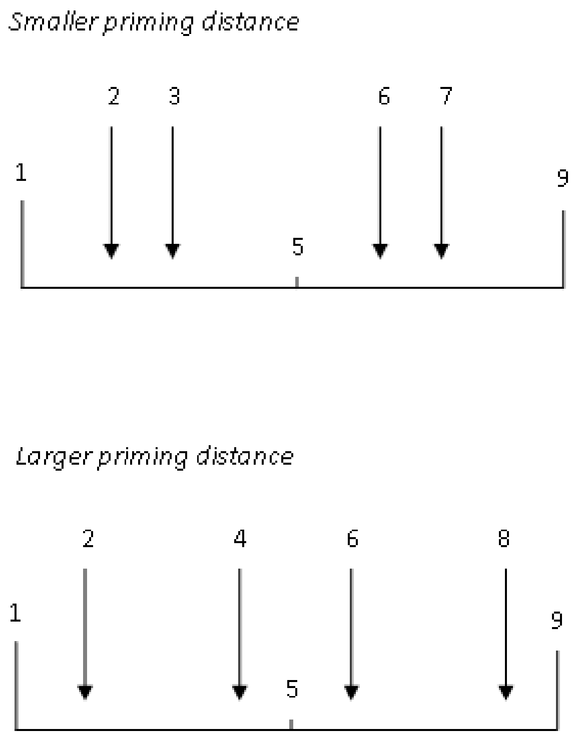

Figure 11: An illustration of the priming distance effect. Performance improves with a smaller numerical distance between prime and target. Performance in the example at the top would therefore be faster and more accurate than the lower example

Van Opstal et al. (2008) investigated whether the priming distance effect reliably implies representational overlap by utilising priming paradigms with both letter and number stimuli, comparing priming distance and congruency effects between the notations. The authors, as in Kunde et al. (2003), questioned theories of representational overlap and response-related processes in explaining priming effects, hypothesising that only a model proposing representational overlap of numbers can account for the priming effect, i.e. when the prime 8 facilitates a response to the target 7. Indeed, the numerical and alphabetical priming tasks demonstrated a comparison distance effect (see Figure 12) and congruency priming effect for both letter and number stimuli. However, a *priming distance effect* (i.e. response activations for a prime affect response to the target: better performance with close-distance pairs) was only observed for the numerical task. Van Opstal et al. (2008) concluded that distance effects during priming paradigms must be interpreted as a comparison distance effect and priming distance effect, particularly as the priming distance effect appears to be unique to numerical priming. Such findings suggest a uniqueness of number priming tasks in demonstrating a distinct representational overlap between numbers, providing a more sensitive and reliable measure of representational overlap than comparison tasks, in which only comparison distance effects can be extracted.

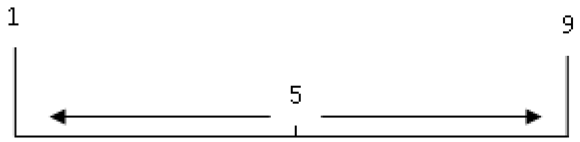

Figure 12: An illustration of the comparison distance effect. As the distance between the comparison number (5) and the prime-target pairs increases, performance improves

4.1.5 Priming in ageing

Numerical priming has been investigated in children and adults, but scarcely in the older adult population. Considering enhanced symbolic discrimination in older age, such a paradigm may be useful in further investigating the effect of ageing on foundational symbolic numerical abilities. Reynvoet et al. (2009) investigated priming effects using a smaller/larger task in children ranging from first to fifth grade (~6-10 years of age), and found similar numerical priming distance and congruency effects between the age groups. However, overall response speed increased with increasing age. The authors suggested that similar congruency effects between age groups may be due to the simplicity of the task (Reynvoet et al., 2009). Faster responses to primed targets with age may reflect increased experience with digits across the lifespan, particularly in early development (Defever et al., 2014; Holloway & Ansari, 2008; Reynvoet et al., 2009). This effect may be especially apparent with smaller digits (1-9), as the frequency with which they are used every day may result in more precise representations (Reynvoet et al., 2009). Such findings of early priming effects demonstrate the nature of numerical representational overlap, even in early development.

In terms of ageing, the direct study of number priming in older adults is scarce, although some data on other forms of priming is available. Howard et al. (1986) investigated the effect of word and non-word primes on older and younger participants' responses to word targets. Stimulus onset asynchronies (SOAs: the interval between prime onset and target onset) were manipulated, and the prime could be semantically related or unrelated to the target (e.g. related trial: 'cat' – 'dog'). Howard et al. (1986) hypothesised that semantic activation (of the prime and surrounding 'nodes') may slow in ageing due to reduced processing speed (Salthouse, 1996), and that older adults may therefore require a longer

SOA to show a priming effect. Older adults did indeed show less pronounced priming effects at the shorter SOA of 150ms compared to younger adults, but similar priming effects at longer SOAs (450 and 1000ms). Further, this effect did not appear to be mediated by a failure to process the prime at shorter SOAs, as older adults performed above chance on a recognition task of the words presented. The authors concluded that ageing may result in a slowing of either the rate at which the prime activates the semantic concept 'node', or the speed at which this activation spreads to neighbouring nodes (generating priming effects). However, some methodological issues may call into question the reliability of the findings. Howard et al. (1986) informed participants of the nature of the study, and used unmasked and therefore consciously processed primes. Studies of numerical priming in adult populations have since used pre and post-masking of primes and faster display times to ensure that primes are processed quickly and/or unconsciously, therefore ensuring the automatic nature of the task.

Fabre and Lemaire (2005) investigated parity judgement in younger and older adults using a 43ms number word prime with either an Arabic digit or number word target, whilst also measuring event related potentials (ERPs). They hypothesised that controlled cognitive processes (e.g. memory tasks) may be affected negatively by ageing, whereas automatic processes may be spared, and therefore that priming effects as an automatic process may be preserved in ageing. Although the older adults were slower overall, both groups demonstrated priming distance and congruency effects. ERPs were found to be larger during incongruent trials for all participants, with the electrophysiological signature of priming effects delayed by 125ms in the older compared to the younger group (Fabre & Lemaire, 2005). There was also a larger difference in the amplitude of waves between congruent and incongruent trials in the younger group compared to the older group, possibly demonstrating a diminished influence of an incongruent prime on processing in the older group (Fabre & Lemaire, 2005). Younger adults showed activation in central and parietal areas, whereas central areas alone were recruited in older adults. Although such neurological differences between age groups were only briefly discussed by the authors, they reflect previous research finding contradictory neurological patterns between younger and older groups during arithmetic problem solving (El Yagoubi et al., 2005), and could alternatively indicate poorer inhibition in the older group (Hedden & Gabrieli, 2004). A tentative explanation for reduced parietal activation for the older adults in Fabre and Lemaire's (2005) study is that older adults may not be directly accessing the meaning of targets to the same extent as the younger group, as the parietal areas (responsible for numerical processing: Piazza & Izard, 2009) were primarily recruited by younger participants during the priming task. Therefore, it would be expected that the parietal areas would also be involved in prime processing for the older group if participants in this group were directly accessing the meaning of each number. Further, the delayed neurological response to incongruent primes in the older group contradicts Howard and colleagues' (1986) theory of slowed activations of numbers and their surrounding ‘nodes’ in ageing. If activations were slowed in the older group, slower responses would be expected for all trials, regardless of congruency (i.e. a general slowing in prime processing: Howard et al., 1986). Therefore, a delayed response to incongruent trials only, and a weaker activation difference between congruent and incongruent trials in the older group during Fabre and Lemaire's (2005) study may not imply slowed spreading activation to nearby numbers (Howard et al., 1986), but rather a reduced ability in the older group to inhibit an incongruent prime (Cappelletti et al., 2014; Dehaene et al., 1998; Hasher & Zacks, 1988; Kramer et al., 1994). Finally, it is possible that such findings reflect varying task strategies between the age groups, possibly due to life experience using and manipulating symbolic numbers in the older group (as in chapter 2: Norris et al., 2015). Such experience may reduce the negative effect of an incongruent prime on older adults’ performances. Finally, half of the trials in Fabre and Lemaire’s (2005) study were cross-notational, presenting a number word prime followed by either a number word or Arabic digit target. Older adults, due to their enhanced symbolic representation of numbers, may have automatically represented number word primes and targets as their corresponding Arabic digit before processing, similar to the non-symbolic to symbolic ‘transcoding effect’: groups with stronger numerical experience and mathematical achievement tend to transcode non-symbolic numerosities into their symbolic (Arabic digit) representation before processing (Castronovo & Göbel, 2012; Norris et al., 2015). Such a process may therefore also serve to explain the contradictory neurological patterns found between younger and older participants. As Fabre and Lemaire’s (2005) study focused on EEG analyses, participant group numbers were relatively low (11 participants in the younger and older groups). Moreover, the priming task used by Fabre and Lemaire (2005) always included a number word prime. Therefore, future research must use larger groups to investigate the impact of ageing on numerical priming effects when using Arabic digit primes, as older adults may demonstrate preserved or even enhanced processing of Arabic digits compared to younger adults.

In a further study, Fabre, Lemaire, and Grainger (2007) investigated the effects of target and prime onset time consistency on younger and older adults' attention. The authors studied masked repetition priming (words or non-words) and categorical numerical priming (cross-notation parity judgement) using either a single and consistent SOA, or a varying SOA. Similar repetition priming effects were found between groups, although the older group were more sensitive to a variable SOA when making category judgements. The authors concluded that such an effect was most likely due to general slowing in the older group (i.e. a processing-speed decline: Salthouse, 1996). Further, the older group showed more eye-blinks during the task, which may have 'unmasked' some of the primes, leading to poorer attentional focus on targets (Fabre et al., 2007) and therefore slower responses. Such findings suggest that although priming effects may be preserved in ageing, older groups may be particularly sensitive to inconsistent SOAs. Fleischman (2007) presented a review of the literature investigating repetition priming effects in older adults and those with Alzheimer's disease (AD), concluding that implicit memory functioning used during repetition priming appears to be preserved in healthy ageing, and that a deficit may indicate early AD (see also Ostergaard, 1994). Although this review investigated repetition priming, it further supports the suggestion of preserved priming effects in healthy ageing. Overall, the literature on the effect of ageing on priming has investigated different forms such as words or categories. Crucially, research directly investigating the effect of ageing on number priming is sparse, and presents contradictory results. Finally, research has not yet attempted to directly investigate the potential of a more embedded symbolic numerical representation in older adults to influence number priming.

4.1.6 The current study

Considering the mixed findings regarding the effect of ageing on basic symbolic numerical abilities, the comparison of number priming abilities using both number word and Arabic digit primes and targets in younger and older adults will add to emerging research on the effect of ageing on foundational symbolic numerical abilities. The use of a priming paradigm allows for further exploration of the nature of numerical representations in older adults. The current study used a number priming task to investigate the effect of ageing on priming distance and priming congruency effects for both Arabic digit and number word stimuli. It is expected that, due to their stronger, more ingrained mental number line and superior symbolic numerosity representation due to lifetime experience with numbers, older adults may show higher overall accuracy on the priming task compared to younger adults (as in chapter 2: Norris et al., 2015; also demonstrated with the SNARC effect: Wood et al., 2008). Secondly, better anchored symbolic representations, and therefore increased automatic access to such representations may lead to increased sensitivity to incongruent primes in ageing, causing a stronger priming-congruency effect for the older group. Therefore, poorer performance may only be expected for the older group on incongruent trials. Finally, older adults may be disadvantaged by a necessity to inhibit an incongruent prime to effectively process a target (Dehaene et al., 1998; Fias et al., 2001; Koechlin et al., 1999), as inhibitory control declines in ageing (Hasher & Zacks, 1988; Kramer et al., 1994). Such a decline has been suggested to affect older adults' performance during a foundational non-symbolic numerical comparison task (Cappelletti et al., 2014), whereby task design requires the inhibition of irrelevant but salient perceptual variables before responding to numerosity (see chapters 2, 5 and 6). It is therefore possible that a similar behavioural pattern may emerge during incongruent priming trials, as the prime must be inhibited to respond correctly to the target (Dehaene et al., 1998). A measure of inhibition will therefore also be administered to investigate possible relationships between inhibitory control and number priming performance. Such analyses will clarify which processes may be responsible for any age differences in number priming. Finally, SOAs will be constant across trials to avoid a negative effect of a variable SOA on older adults' performance (Fabre et al., 2007).

4.2 Methods

4.2.1 Participants

40 participants were recruited: 20 older adults aged 62 - 70 (M = 65, SD = 2.9; 14 females) and 20 younger adults aged 18 - 24 (M = 20, SD = 1.8; 16 females).

4.2.2 Materials

Control measures included the Mini Mental State Exam (MMSE), Geriatric Depression Scale (GDS), Spelling, Calculations (see p.28, chapter 2 for a detailed discussion of these materials), Colour Stroop, and Number Stroop (see below).

4.2.3 Procedure

Data for the current study were collected alongside data for chapter 6 in a partially counterbalanced manner, as the digit and number word priming tasks were completed at the beginning and end of the testing session to avoid carry-over effects. Participants from the younger and older groups took part in the same tasks. All computerised tasks were viewed from a distance of 57cm, on a screen with a 1280x1024 resolution and 90Hz refresh rate. Computerised tasks were conducted using E Prime 2.

4.2.4 Priming tasks

Two priming tasks based on paradigms by Dehaene et al. (1998) and Van Opstal et al. (2008) were used. The first task included Arabic digits as primes and targets, and the second task included number words as primes and targets. For each task, stimuli were displayed in white on a black background in Courier New font pt 32. The task was to decide whether a target number between 1 and 9 (excluding 5) was smaller or larger than the fixed standard (5). Therefore, the numerical distance between a prime and a target was 1, 2 or 3. Participants responded with the keyboard, pressing 'A' for smaller and 'L' for larger. Each trial began with a fixation '+' (1000ms), followed by a premask '###' (100ms). The prime (Arabic digit or number word) then appeared for 43ms (as in Dehaene et al., 1998; Fabre & Lemaire, 2005), immediately followed by a postmask '###' (100ms). Finally, the target appeared on screen until a response was detected. A 1000ms interval preceded each new trial (see experimental procedure in Figure 13). Although primes were presented very briefly, they should be processed at a high cognitive level (Dehaene et al., 1998; Koechlin et al., 1999; Kunde et al., 2003; Reynvoet & Brysbaert, 1999), even when rendered invisible by interocular suppression (Bahrami et al., 2010) or processed unconsciously (Kunde et al., 2003; see Van den Bussche, Van den Noortgate, & Reynvoet, 2009 for a review). A 43ms prime was therefore used in the current study (as in Dehaene et al., 1998), to ensure that the prime was processed automatically and unconsciously. Participants were instructed to respond to the larger/smaller status of the target as quickly and as accurately as possible. Each priming task (digit or word) consisted of 20 practice trials randomly generated from test stimuli, followed by two blocks of 96 experimental trials (192 trials per notation). Accuracy and RTs were recorded. Analyses will investigate the comparison distance, congruency priming, and distance priming effects (Van Opstal et al., 2008).

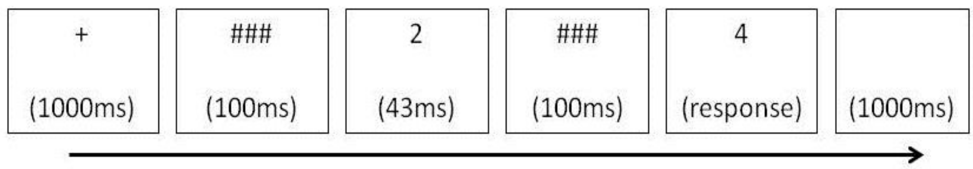

Figure 13: The experimental procedure for the digit priming task

4.2.5 Inhibition tasks

The classic colour Stroop (Stroop, 1935) and number Stroop tasks measured inhibition. For the colour Stroop, participants in a speeded task read a list of black-ink (neutral) colour words, followed by naming coloured dots (also neutral). Participants then identified the ink colour of incongruent coloured words (e.g. 'RED' in blue ink). The Stroop effect was calculated by subtracting mean speed in the neutral tasks from speed in the incongruent task. The number Stroop paradigm consisted of a magnitude and a physical task: in the magnitude task, participants chose the side of the screen containing the largest number in magnitude ('Q' = left, 'P' = right). In the physical task, participants chose the side containing the physically larger number (Cohen Kadosh et al., 2008). Arabic digits from 1 to 9 (excluding 5), appeared in the centre of the screen in Courier 27pt (0.6^o) and 32pt (0.8^o) at a horizontal visual angle of 10^o. Stimuli were grouped into three distance bins (the numerical distance between the stimuli pairs): 1, 2 and 5. The practice block contained 36 trials, with the pairs [4-5] and [5-6] in distance bin 1, [3-5] and [5-7] in distance 2, and [4-9] and [1-6] in distance 5 (practice trials included novel pairs, but this was not possible for distance bin 5, as in Cohen Kadosh et al., 2008). There were 72 trials in each condition: congruent, neutral and incongruent (216 total). During a congruent trial, the numerically larger number was also largest in terms of physical size (e.g. 4 – 9). During an incongruent trial, the numerically larger number was the smallest in physical size (e.g. 4 – 9). Neutral trials varied by task type: in the physical task, a neutral trial consisted of two identical Arabic digits in different physical sizes (e.g. 3 – 3). In the magnitude task, neutral trials consisted of pairs of different Arabic digits of the same physical size (e.g. 3-7). A fixation cross (+) first appeared for 300ms, followed by a 500ms delay. Stimuli then appeared for up to 5000ms until response, followed by a 1500ms interstimulus interval preceding the next trial.

4.3 Results

Accuracy for all participants was near ceiling (99%). However, the younger group were less accurate overall (M = 97.7%, SD = 1.49) than the older group (M = 99.5%, SD = .57; $t(24.42) = -4.956$, $p < .001$), reflecting higher overall symbolic comparison accuracy found in chapter 2. Therefore, analyses on correct RTs only will follow (e.g. Dehaene et al., 1998). RT outliers were removed by applying individual 3xSD cut offs (1.7% of data removed). Where sphericity was violated, Greenhouse Geisser corrections were applied.

4.3.1 Comparison distance effect

The comparison distance effect refers to the function of the distance between the prime-target pair and the standard (5). As in Van Opstal et al. (2008), but with the addition of age group as a between-subjects factor, a 2 (notation: word/digit) x 2 (size: smaller or larger than 5) x 4 (Distance from standard: 1,2,3,4) x 2 (age group) mixed ANOVA was conducted on correct RTs for identical prime-target trials to negate the effect of priming distance. There was a main effect of notation, $F(1,37) = 35.26$, $p < .001$, with slower RTs in the number words task (M = 581ms, SD = 157) than the Arabic digits task (M = 511ms, SD = 123: e.g. Koechlin et al., 1999). Further, there was a classic main effect of distance, $F(3,111) = 20.03$, $p < .001$, with RTs decreasing with increasing distance from the standard (5): Distance 1 M = 578, SD = 150, Distance 2 M = 545, SD = 151, Distance 3 M = 535, SD = 142, Distance 4 M = 527, SD = 129 (e.g. Dehaene et al., 1998; Reynvoet, Brysbaert, et al., 2002; Reynvoet, Caessens, et al., 2002). There was also a main effect of size (whether the prime and target were smaller or larger than the standard 5; $F(1,37) = 6.81$, $p < .05$): overall, participants responded faster to prime-target combinations under 5 faster (M = 539ms, SD = 141) than those over 5 (M = 554ms, SD = 148), reflecting the classic size effect (Dehaene, 1997). Older adults responded slower overall (M = 575ms, SD = 134) than younger adults (M = 518ms, SD = 148; $F(1,37) = 6.35$, $p < 05$), likely due to slower processing speed (Cappelletti et al., 2014; Christensen, 2001; Howard et al., 1986; Salthouse, 1996). Further, there was an interaction between size and age group ($F(1,37) = 13.82$, $p < .01$). Paired samples *t*-tests reveal that this interaction appears due to similar RTs for targets smaller and larger than 5 in the younger group ($p = .452$), whereas older adults were significantly slower to respond to targets over 5 (M = 592ms, SD = 82) compared to those under 5 (M = 556ms, SD = 80; $t(19) = -5.175$, $p < .001$). Such analyses therefore suggest that the size x age group interaction appears due to older adults' slower responses to targets larger than 5 than those smaller than 5, reflecting a classic size effect in the older group alone.

4.3.2 Congruency priming effect

The congruency priming effect refers to the effect of the congruency of the prime on response to the target. Trials with identical prime-target pairs were excluded to negate the effects of perceptual priming (Van Opstal et al., 2008). A 2 (notation) x 2 (target size: smaller or larger than 5) x 2 (congruency) x 2 (age group) mixed ANOVA was conducted on RTs for correct trials. There was a main effect of congruency, with faster responses to congruent (M = 571ms, SD = 146) than to incongruent trials (M = 591ms, SD = 133; $F(1,38) = 63.05$, $p < .001$). An interaction between congruency and age group ($F(1,38) = 10.68$, $p < .01$) was investigated with separate ANOVAs per group, however the congruency effect remained for all participants. Therefore, to further investigate the nature of the congruency x age group interaction, independent *t*-tests were conducted for each group between RTs on congruent and incongruent trials. RTs were slower in the older group compared to the younger group for incongruent trials (older M = 619ms, SD = 119; younger M = 562ms, SD = 140; $t(38) = -2.979$, $p < .01$), but the group difference for congruent trials was marginally non-significant ($p = .053$). The congruency x age group interaction therefore appears primarily driven by older adults' particular sensitivity to incongruent primes compared to younger adults, with similar performances between groups on congruent trials (see Figure 15).

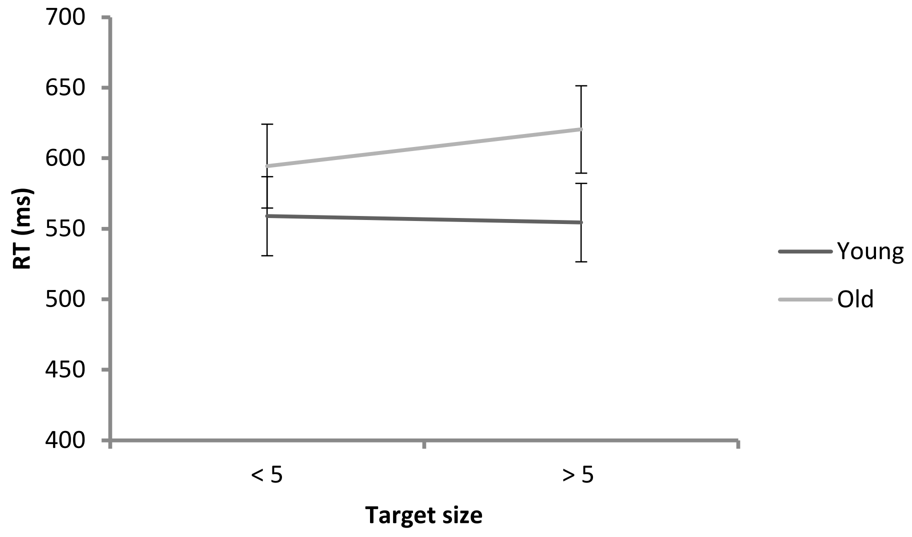

Figure 14: Mean RTs of each age group during trials with a target smaller or larger than 5

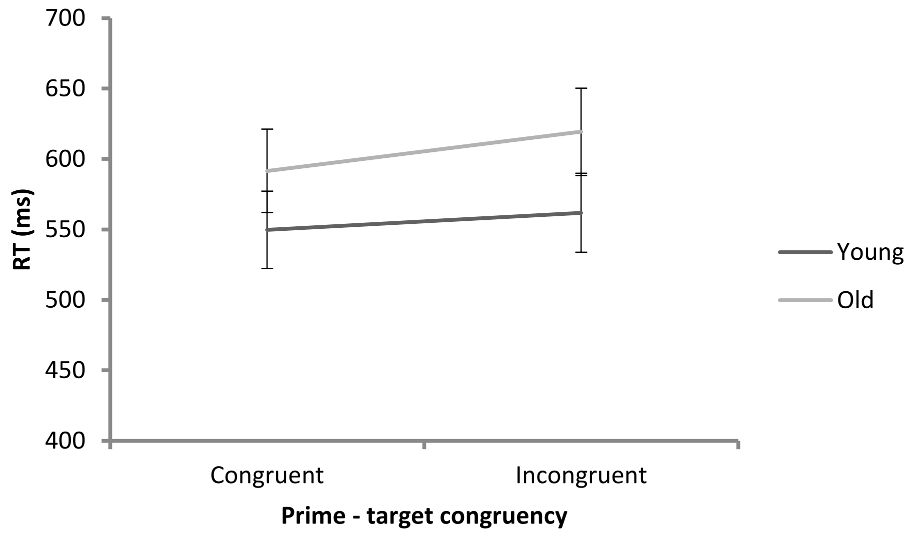

Figure 15: Congruency priming effects in the younger and older groups

4.3.3 Priming distance effect

The priming distance effect refers to the effect of the distance between the prime and target. A 2 (notation) x 2 (target size) x 3 (priming distance: 1, 2, or 3) x 2 (age group) mixed ANOVA was conducted on correct RTs for congruent trials. As before, there were main effects of notation and size, and an interaction between size and age group. Further, there was a main effect of priming distance ($F(1.55,58.96) = 9.22$, $p < .01$), with slower RTs with increasing distance between the prime and target (distance 1: M = 563ms, SD = 11; distance 2: M = 577ms, SD = 11; distance 3: M = 583ms, SD = 12). There was a significant interaction between size and priming distance ($F(1.81,68.58) = 3.861$, $p < .05$). Contrasts indicate that this interaction appears due to similar distance effects for all targets (both smaller and larger than 5) when the distance between prime and target is 1 or 2 ($p = .289$). However, with a larger prime-target distance of 3, there was a significant difference between the distance effect dependent on whether the target was smaller or larger than 5, ($F(1,19) = 7.114$, $p = .015$: targets smaller than 5; distance 2 M = 571ms, SD = 141, distance 3 M = 573ms, SD = 142; targets larger than 5; distance 2 M = 583ms, SD = 153, distance 3 M = 592ms, SD = 152). Therefore, the priming distance effect appears to be stronger at larger prime-target distances when the target is larger than 5 compared to when the target is smaller than 5 (see Figure 16). All other interactions were non-significant ($p_s > .05$).

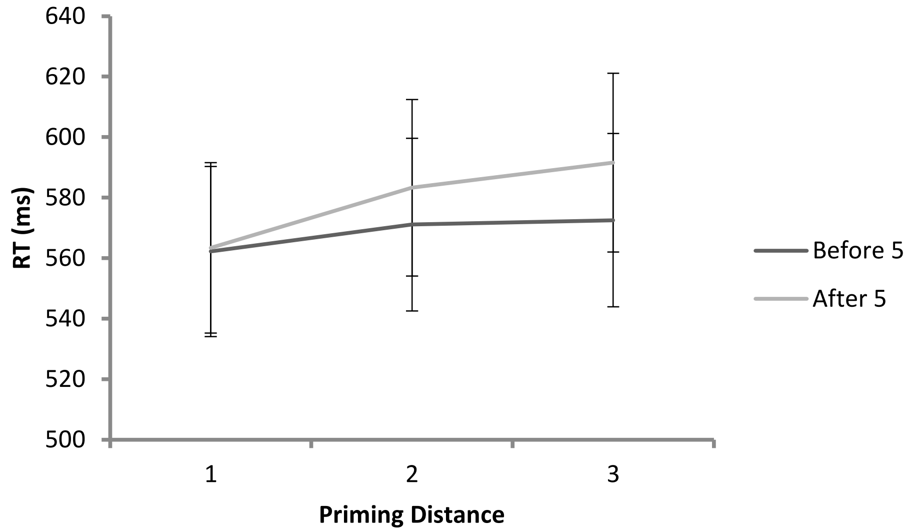

Figure 16: Priming distance effects for targets smaller or larger than 5

4.3.4 Control measures and correlations

Group differences on control measures are reported here and in chapter 6, as the same participants completed both studies. An interference effect (RT on incongruent trials – RT on neutral trials) was calculated for correct trials on the magnitude number Stroop task. The physical number Stroop data was excluded from all analyses as performance on the task did not reflect the usual distance effect (e.g. Cohen Kadosh et al., 2008). This suggests that the Stroop nature of the task may have been compromised. Independent *t*-tests were conducted between the younger and older adults on years of education, spelling, mathematical achievement (MA), and colour and number Stroop interference. Years of formal education were similar between groups (older adults: M= 16.5, SD= 2.6; younger adults: M= 16.2, SD= 1.7; $p > .280$). Older adults scored higher on the spelling task (M = 82.46%, SD = 10.26) than younger adults (M = 74.29%, SD = 6.58; $t(37) = -2.97$, $p = .005$). The same pattern applied to mathematical achievement, with older adults achieving higher scores (M = 88.38%, SD = 8.46) than younger adults (M = 69.77%, SD = 12.66; $t(33.29) = -5.43$, $p < .001$), reflecting the findings from chapter 2. Finally, older adults demonstrated a larger interference effect during the colour Stroop task (M = 15.05s, SD = 5.30) than younger adults (M = 7.20s, SD = 2.9: $t(27.58) = -5.70$, $p < .001$), reflecting inhibitory decline with ageing (Cappelletti et al., 2014; Hasher & Zacks, 1988). However, there was no significant difference between groups on number Stroop interference ($p > .1$).

Control measures were correlated with the interference effect of an incongruent prime (mean RT on 'same' trials, e.g. prime = 2 and target = 2, - RT on incongruent trials) separately for young and older adults to investigate the relationship between congruency priming and other cognitive abilities in ageing. The priming interference effect was therefore entered into separate correlations per group with number Stroop interference, colour Stroop interference, spelling, and MA. In the younger group, no correlations reached significance ($p_s > .1$). In the older group, there were no significant correlations between the priming interference effect and control measures ($p_s > .1$). However, higher spelling scores correlated with superior mathematical achievement ($r = .583$, $p = .007$), and with reduced number Stroop interference ($r = -.492$, $p = .028$), reflecting better inhibitory control in older adults with superior general cognitive ability.

4.4 Discussion

The current study aimed to investigate numerical priming effects in younger and older adults to further investigate the effect of ageing on foundational symbolic numerical abilities. Previous research has mostly focused on the impact of ageing on exact abilities such as counting, arithmetic, and problem-solving strategies, with such studies producing contradictory results. More recent research specifically investigating foundational symbolic numerical abilities in ageing has found preserved or even enhanced symbolic comparison task performance in older adults using both single digit (Cappelletti et al., 2014) and two-digit numbers (chapter 2: Norris et al., 2015). Indeed, in chapter 2 foundational symbolic comparison abilities were found to be enhanced in ageing, with older age contributing to such superior performance over and above higher mathematical achievement (Norris et al., 2015). Crucially, older adults presented a less pronounced symbolic distance effect than the younger adults, suggesting stronger foundational symbolic numerical abilities with ageing. Such a significant contribution of older age to enhanced foundational symbolic skills was suggested to be the result of lifetime experience using and manipulating numbers (e.g. Defever et al., 2014). In the current study, older adults were more accurate overall than younger adults. Further, older adults appeared to be more sensitive to the effect of an incongruent prime. Finally, older adults demonstrated a size effect, with slower responses to larger numbers (>5) than to smaller numbers (<5), regardless of congruency. Such a size effect was not observed for the younger group. The findings may be interpreted to support the conclusions from chapter 2 that older adults demonstrate a more embedded symbolic numerical representation, resulting in deeper processing of primes (stronger interference effects) and targets (stronger size effects) compared to younger adults. On the other hand, the absence of a size effect for the younger group may indicate faster and more efficient access to symbolic numerical representations in the younger group unhindered by effects of size. Additional research is required to further investigate possible mechanisms behind increased size effects coupled with stronger interference effects for older compared to younger adults during a numerical priming task.

Older adults were slower overall compared to younger adults, reflecting results from similar studies (Fabre & Lemaire, 2005; Fabre et al., 2007; Howard et al., 1986), likely due to reduced processing speed in older age (Christensen, 2001; Deary et al., 2009; Hedden & Gabrieli, 2004; Salthouse, 1996; Salthouse & Kersten, 1993). Further, the congruency priming effect impacted older adults' performance, whilst younger adults showed no such effect. Such a finding contradicts previous research using priming in other notations such as words (e.g. Howard et al., 1986), whereby weaker priming effects were found for older adults. However, Howard et al. (1986) found *reduced* priming effects in older participants when stimulus onset time was short (150ms). The current findings do not support these results, as not only were priming effects stronger for the older group, but this effect was maintained even when using short prime (43ms) and masking times (100ms). Howard et al. (1986) proposed that the spreading of activation between related semantic nodes may be slowed in ageing, reducing priming effects in older participants (but see Lustig, Hasher, & Zacks, 2007). Although the authors claim to refute the suggestion that effortful processes may decline in ageing, they suggest that their findings question the robustness of automatic processing in ageing due to deficits in priming at the shortest SOA. However, the current findings suggest that numerical priming effects are observed in normal ageing, even with short SOAs, potentially due to a combination of stronger and more embedded symbolic numerical representations and poorer inhibitory control in older age. Finally, it is unclear to what extent findings of non-numerical word tasks can be applied to the current study using numerical stimuli. That older adults demonstrated a stronger negative effect of an incongruent prime compared to younger adults in the current study may reflect a more embedded symbolic numerical representation in the older group as a result of lifetime experience with numbers (Defever et al., 2014, as in chapter 2). Indeed, small numbers in particular may be represented more precisely due to their frequent and repeated use (Reynvoet et al., 2009), with older adults having more lifetime exposure, and therefore repeated use, compared to younger adults. It is therefore possible that older adults' more embedded numerical representations caused a stronger effect of an incongruent prime, and led to stronger size effects. As participants must inhibit an incongruent prime before correctly responding to a target (Dehaene et al., 1998), and inhibitory control declines in ageing (Cappelletti et al., 2014; Hasher & Zacks, 1988), particularly in terms of inhibiting a strong behavioural-motor response (Kramer et al., 1994), it could be suggested that stronger congruency effects in the older group are due to reduced inhibitory control with age. However, correlational analyses between priming performance and interference effects suggest that declined inhibition in ageing as measured by the number and colour Stroop tasks may not be responsible for stronger priming congruency effects in the older group. The results may therefore not to be mediated by older adults' poorer inhibitory control, or may be related to other forms of inhibition not measured in the current study.

In a further study investigating cross-notation parity judgement in younger and older adults, Fabre and Lemaire (2005) found delayed ERPs to incongruent trials in the older group. To what extent this effect may be mediated by the cross-notational design of the experiment, and the potential of transcoding, is unclear. Due to increased lifetime experience with numbers, older adults may be more likely to 'transcode' number-word stimuli into an Arabic digit before processing, similar to the suggestion that non-symbolic numerosities are transcoded into Arabic digits by those with higher mathematical experience (e.g. mathematicians: Castronovo & Göbel, 2012; and older adults in chapter 2). If older adults transcode number words into Arabic digits more frequently and automatically than younger adults, this may explain the different ERPs to incongruent primes between groups found by Fabre and Lemaire (2005). However, congruency effects were found by Fabre and Lemaire (2005) in both age groups, supporting the preservation of priming effects in healthy ageing (Ballesteros, Reales, & Mayas, 2007; Fleischman, 2007). In a further study, similar repetition priming effects were found between younger and older adults (Fabre et al., 2007), although the older group were more sensitive to a variable SOA. In the current study, using a consistent SOA and similar experimental paradigms to previous number priming studies (Dehaene et al., 1998; Van Opstal et al., 2008), priming effects were found for the older group, reflecting previous research (Fabre & Lemaire, 2005; Fabre et al., 2007). Indeed, such effects were stronger for the older adults compared to younger adults, possibly supporting ERP data from older adults in previous research showing a delayed response to incongruent primes (Fabre & Lemaire, 2005). Numerical priming effects therefore appear to be preserved in ageing. Further, an incongruent prime may produce a stronger effect for older compared to younger adults due to their more embedded representation of symbolic number.

In addition to a stronger effect of an incongruent prime on older adults' performances, older adults were also slower to respond to targets over 5 compared to those under 5, regardless of congruency. Conversely, the younger group showed similar RTs for targets smaller and larger than 5. These results suggest the presence of a size effect for the older group, but not for the younger group, possibly due to older adults' better anchored symbolic representations (supporting the findings of chapter 2). Moreover, a steeper priming distance effect was found for prime-target combinations over 5 for the older group only. Such a pattern of results further support the notion of stronger size effects in the older compared to the younger group, likely due to older adults' more embedded representation of number, in that numerical representations become less precise with increasing magnitude (Dehaene, 1997; Piazza & Izard, 2009). A more embedded numerosity representation may therefore increase the strength of representational overlap between larger numbers, and may also explain increased priming distance effects on targets over 5 for the older group. The results from the current study therefore support the conclusions in chapter 2; that older adults demonstrate a more strongly embedded and better anchored symbolic numerical representation due to their lifetime exposure to numbers. This may be particularly relevant to small numbers, which are experienced frequently in everyday life (Reynvoet et al., 2009). Finally, it is important to note that older adults were significantly more accurate overall compared to younger adults. This finding may be attributed to higher accuracy during symbolic numerical tasks in older adults due to more embedded symbolic numerical representations (supporting chapter 2). However, it may possibly indicate under-performance in the younger group, or even higher performance in the older group due to stronger motivation. Indeed, in this study, as with many psychological studies, younger adults were recruited through the Department of Psychology, whereby they were expected to take part in research studies for partial course credits. Older adults, however, participated voluntarily after seeing recruitment posters in public places in the local community. Future research should aim to investigate the role of motivational differences between age groups in potentially facilitating performance for older adults during psychological tasks.

In conclusion, the current findings reflect those of chapter 2, that foundational symbolic numerical abilities appear to be preserved and potentially enhanced in healthy ageing. Priming effects, as a foundational, automatic numerical ability appear to be preserved in ageing (as in Fabre & Lemaire, 2005; Fabre et al., 2007; but see Howard et al., 1986 for semantic priming). The current findings suggest that older adults may be more susceptible to the influence of an incongruent prime. It remains unclear at which stage during a priming paradigm older adults' processing may deviate from that of younger adults. If older adults have better anchored numerical representations, these may be more readily and automatically accessible and activated, resulting in greater sensitivity to priming. Therefore, an incongruent prime has a stronger impact on older adults' performances compared to younger adults. A further suggestion is that both older and younger adults prepare a response to a prime (Dehaene et al., 1998), but older adults may have more difficulty inhibiting this prepared response when the prime is revealed to be incongruent (Hasher & Zacks, 1988; Kramer et al., 1994). However, no correlations were found between interference effects and priming task performance. Further, older adults' more refined numerical representations appear to increase the strength of their size effect, regardless of congruency. This finding further supports a more embedded numerical representation with increasing age. However, more research is required to further investigate the nature of a more embedded symbolic numerical representation in older age. Future research would benefit from comparing the current findings with a parity judgement priming task, as well as the inclusion of a battery of inhibition measures (Fuhs & McNeil, 2013) which may help to uncover which specific inhibitory functions may be necessary during number priming, particularly in ageing. Indeed, the addition of a go/no-go style inhibition task may reveal more about the nature of inhibiting a motor response prepared to a prime in ageing. Moreover, future research should aim to investigate the nature of stronger size effects in older age. However, this is the first study to directly investigate number priming in older and younger adults whilst also investigating the impact of inhibitory control on performance. The findings contribute further evidence for better anchored foundational symbolic numerical abilities in ageing, in addition to demonstrating stronger priming-congruency and size effects in older adults, possibly as a result of more ingrained numerical representations due to lifetime experience with numbers (as with the SNARC effect: Wood et al., 2008) and due to poorer inhibitory control in ageing (Hasher & Zacks, 1988).

5 Chapter 4: Investigating the effect of higher education in mathematics on foundational numerical abilities in ageing

5.1 Introduction

5.1.1 Contribution of the current chapter

The current chapter builds on chapters 2 and 3, where preserved foundational non-symbolic abilities and superior foundational symbolic numerical abilities were found in ageing. Enhanced symbolic numerical processing in ageing appears to be primarily driven by increasing age, rather than older adults' superior arithmetical ability. Foundational non-symbolic numerosity discrimination acuity appears to be preserved in ageing due to its embedded nature. However, the older participants demonstrated a stronger ratio effect on response times than the younger group, possibly due to the older adults transcoding non-symbolic stimuli into their symbolic counterparts prior to processing a response, as suggested for mathematicians, who presented similar results (Castronovo & Göbel, 2012). This similar behavioural pattern to that seen in mathematicians further supports the suggestion that older adults' superior symbolic numerical representation (as demonstrated by their stronger foundational symbolic skills) may be due to lifetime experience with numbers, in that they behave similarly to another group with superior numerical experience (mathematicians). Furthermore, the contribution of mathematical achievement in the younger and older groups to foundational numerical abilities was investigated in chapter 2, with a link in both groups found between mathematical ability and symbolic, but not non-symbolic foundational abilities.

Previous research with participants across the lifespan has found links between mathematical abilities and symbolic (Mussolin, Nys, Leybaert, & Content, 2012; Newton, Waring, & Penner-Wilger, 2014) and non-symbolic comparison task performance (Halberda

& Feigenson, 2008; Halberda et al., 2012; but see Castronovo & Göbel, 2012; Gilmore et al., 2013; Inglis et al., 2011). However, in chapter 2 mathematical achievement was not found to be related to non-symbolic numerical acuity in either age group, reflecting the contradictory findings of previous research on the link between ANS acuity and mathematical achievement in adults (as in Castronovo & Göbel, 2012; Inglis et al., 2011). However, similar previous studies have found a link between non-symbolic abilities and mathematical achievement in ageing (Cappelletti et al., 2014). Therefore, in order to further investigate the nature of preserved non-symbolic and enhanced symbolic foundational numerical abilities in ageing, and to what extent such findings may be attributed to other factors such as superior mathematical achievement and experience in older adults, the current study aimed to investigate foundational numerical abilities in a group of older adults with even higher levels of mathematical experience. Experimental paradigms from chapter 2 were administered to a group of older adults with a degree in mathematics. Such a group may be assumed to possess further strengthened mathematical skills compared to older adults with higher education in mathematics (Castronovo & Göbel, 2012). Indeed, younger adults with a higher education in mathematics have been found to present stronger symbolic accuracy, as well as stronger ratio effects on RTs during non-symbolic comparison (Castronovo & Göbel, 2012), as found for older adults in chapter 2. Repeated exposure to symbolic number, as well as practice in accessing and manipulating the semantic meaning of Arabic digits during a mathematics degree may lead to further embedding of symbolic numerical representations. Therefore, this study will address the question of the impact of mathematical experience on foundational numerical abilities in ageing, by comparing such abilities between a group of older adults with high numerical experience due to lifespan exposure to numbers, and a group of older adults with even higher and more specialised levels of experience with numbers due to a specific higher education in mathematics. Such analysis will investigate to what extent symbolic foundational numerical abilities may be enhanced in ageing due to lifetime experience with numbers, and to what extent preserved non-symbolic foundational skills in older adults may be attributed to the preservation of a core, innate cognitive system (Dehaene, 2009). Indeed, if older adult mathematics alumni demonstrate superior foundational non-symbolic and symbolic numerical skills, it could be suggested that foundational numerical abilities are preserved in ageing due to the effect of lifespan exposure to and experience with numbers. It could also be concluded that higher mathematical education and therefore even further enhanced numerical experience across the lifespan may provide a protective effect for foundational numerical skills in ageing (i.e. not only are the alumni's non-symbolic abilities preserved, but enhanced compared to older adults without higher mathematical education). On the contrary, should the alumni group show similar foundational numerical acuity to the control group, it could be concluded that foundational numerical abilities are preserved in ageing due to their innate, embedded nature (Dehaene, 2009; Piazza et al., 2004), and are not enhanced in ageing by increased exposure to explicit mathematical education (alumni group) or due to lifespan experience with numbers (control group).

5.1.2 Mathematical ability and the approximate number system

In recent years, interest has grown regarding a possible link between foundational non-symbolic numerical processing, namely the Approximate Number System (ANS: Dehaene, 1997; Halberda et al., 2008) and achievement in mathematics (for a review see Chen & Li, 2014). Evidence for a foundational role of ANS acuity in the development of symbolic numerical understanding and mathematical achievement is supported by studies finding impaired ANS acuity in individuals suffering from the specific mathematical learning difficulty dyscalculia (Piazza et al., 2010), with poorer ANS acuity related to their weakness in mathematical and numerical operations. However, although a correlation between foundational non-symbolic numerical skills has been frequently demonstrated in children (e.g. Halberda & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2011; Libertus, Odic, & Halberda, 2012; Mazzocco, Feigenson, & Halberda, 2011; but see Fuhs & McNeil, 2013; Gilmore et al., 2013; Göbel, Watson, Lervåg, & Hulme, 2014), the link in adults is less clear, with some researchers finding a relationship between ANS acuity and mathematical achievement (Halberda et al., 2012), and others failing to replicate such a link (Castronovo & Göbel, 2012; Inglis et al., 2011; chapter 2: Norris et al., 2015). Even in adults with a higher education in mathematics, a relationship between such basic non-symbolic numerical processes and mathematical ability may not be replicated (Castronovo & Göbel, 2012). However, Castronovo and Göbel (2012) found a link between higher mathematical achievement and better symbolic skills, as well as more efficient mapping between non-symbolic and symbolic numerical quantities. On the contrary, Lindskog, Winman, and Juslin (2014) compared the ANS acuity of undergraduates in different disciplines, and found a non-significant trend toward superior ANS acuity in students of mathematics compared to those studying business or humanities subjects. However, an improvement in ANS acuity between the first and third year of undergraduate study (i.e. with increasing higher education) was confined to the business studies group only, with the effect of explicit further education in mathematics remaining unclear. Although this study provides some evidence for an effect of increased mathematical education on ANS acuity, the authors deliberately did not use congruent and incongruent trials to avoid creating a 'Stroop-like effect' (Gilmore et al., 2013; Szűcs et al., 2013). Without such controls, it cannot be ruled out that participants may have been using a non-numerical system other than the ANS to make a quantity judgement (i.e. are the blue or yellow dots largest?). Investigation of ANS acuity in groups with enhanced mathematical education and training may further explore the nature of the relationship between ANS acuity and mathematical achievement. Moreover, further investigation of both basic non-symbolic and symbolic numerical abilities in participants with further mathematical education may shed further light on the possibility that, at least in adults, links between mathematical skills and basic numerical abilities may be confined to symbolic numerical abilities alone (e.g. Castronovo & Göbel, 2012). As individuals with dyscalculia show poorer symbolic numerical comprehension, alongside a specific ANS deficit related to their problems with mathematics, on the opposite end of the ability spectrum mathematically educated adults, particularly those older alumni who benefit from the addition of lifetime experience with numbers, may be expected to demonstrate superior symbolic numerical abilities and ANS acuity over those without higher mathematical education.

In the first study to investigate the impact of a higher education in mathematics on foundational non-symbolic and symbolic numerical abilities, Castronovo and Göbel (2012) studied the impact of specialised mathematical education on foundational numerical skills and their relationship with mathematical achievement. The authors utilised a comprehensive set of experiments, including measurement of participants' precision of mapping between non-symbolic and symbolic numerical representations, in a group with a higher education in mathematics and a group with an alternative higher education (Psychology students). Castronovo and Göbel (2012) found similar ANS acuity between the groups, and also found that the ANS did not correlate with mathematical achievement in either group. However, participants with a further education in mathematics showed stronger foundational symbolic skills, with a reduced distance effect on performance, and further appeared to benefit from stronger mapping abilities between non-symbolic and symbolic numerosities (e.g. presenting smaller coefficients of variance when approximately matching a set of dots to a corresponding Arabic digit). Such superior mapping abilities appeared to lead to stronger distance effects on response speed in the non-symbolic discrimination task, as the mathematicians may have adopted the additional step of transcoding non-symbolic stimuli into their symbolic counterparts. Therefore, although participants with higher mathematical ability demonstrated superior mapping between non-symbolic and symbolic representations of number, as well as superior automatic access to symbolic representations of non-symbolic quantities, this strength did not lead to superior ANS acuity or to a relationship between mathematical achievement and the ANS. It was concluded that, although explicit mathematical education may enhance mapping precision between non-symbolic and symbolic numerical representations, further mathematical achievement did not lead to enhanced ANS acuity (Castronovo & Göbel, 2012). The authors suggest that although ANS acuity appears to correlate with retrospective mathematical achievement measures in some studies with children (e.g. Halberda & Feigenson, 2008), ANS acuity may reach a maximum in adulthood, potentially reducing a correlation, even where participants are highly educated in mathematics.

In a similar vein, Guillaume, Nys, Mussolin, and Content (2013) studied numerosity and surface area discrimination acuity (as in Lourenco, Bonny, Fernandez, & Rao, 2012) in adults with varying mathematical education levels by comparing such abilities in Psychology (lower mathematical content) and Engineering students (higher mathematical content). Guillaume et al. (2013) measured numerical and surface area discrimination acuity using a classic non-symbolic numerosity comparison task in which participants decided which dot set is most numerous or which set has a larger area respectively. In their design, the non-symbolic stimuli (dots) were size controlled with three levels: congruent, incongruent, and anticorrelated. Contrary to the findings of similar ANS acuity between groups by Castronovo and Göbel (2012), Engineering students demonstrated higher ANS acuity compared to Psychology students. Further, the higher mathematical achievement group (Engineers) were more negatively affected by the irrelevant dimension of numerosity during the area comparison task than those with lower mathematical ability (Psychologists). Conversely, the Psychology students (lower mathematical achievement) were more affected by the irrelevant dimension of area during numerosity discrimination than those with higher mathematical attainment (Engineers). The authors concluded that due to prolonged exposure to numbers, Engineering students may perceive numerical cues as more salient than other perceptual cues such as dot size and area, providing them with a more precise ANS but more interference from numerosity when area discrimination is required. Guillaume et al. (2013) suggested that their results may contradict those of Castronovo and Göbel (2012) due to varying experimental methods (e.g. sequential vs. paired dot displays, controls of perceptual variables). However, it is possible that the perceptual controls utilised by Guillaume et al. (2013) may have increased the inhibitory load of the task, due to a higher proportion of incongruent trials (incongruent and anticorrelated: Clayton & Gilmore, 2014; Fuhs & McNeil, 2013; Gilmore et al., 2013). It is possible therefore that the Engineers' superior ANS acuity may be due to their stronger ability to inhibit salient but contradictory information during incongruent trials (Cipora et al., 2015). Further, the analyses by Guillaume et al. (2013) suggest that one participant presented a Weber fraction (*w*) outlying by over four standard deviations from the group mean. Although the impact of this outlier on correlational analyses is discussed by the authors, its effect on group differences in ANS acuity is unclear. Participants presenting outlying w_s from the group mean are often excluded (e.g. Halberda et al., 2012), as it cannot be guaranteed that the participant has understood or performed the task correctly. Therefore if such an outlier was included in the primary analyses it is possible that the reliability of the findings may be reduced.

Finally, in investigating the effect of mathematical education on foundational symbolic numerical representations, Cipora et al. (2015) recently investigated the effect of mathematical expertise on the magnitude of the SNARC effect. Final year PhD candidates engaged in using higher order and abstract mathematical concepts in their everyday work were chosen as the high-math experience group, to be compared with a group of PhD-level engineers (medium mathematical experience) and humanities students (lower mathematical experience). Using a parity judgement task, the authors found a SNARC effect for all participants except the mathematicians. Indeed, the slope of the SNARC effect decreased with increasing mathematical experience (the SNARC effect was less pronounced in the engineering group compared to the humanities group, and absent for the mathematicians compared to the engineers). Cipora et al. (2015) provided some possible explanations for the diminished SNARC effect in professional mathematicians. Firstly, it was suggested that, alongside increased fluid intelligence in such groups, mathematicians may also benefit from stronger inhibitory control, possibly reducing the interference of an 'incongruent' trial in creating a SNARC effect (e.g. when making a 'larger' response with the left hand is required). Further, mathematicians may have progressed toward a more abstract concept and processing of numbers, possibly reducing the influence of the cultural and developmental numerical representation of small numbers to the left and large numbers to the right, as is necessary to detect a SNARC effect. Finally, the use of a parity judgement task inherently reduces the necessity to represent and process magnitudes on a spatial number-line continuum, as only processing of the parity status of the number is required. Therefore, if automatic numerosity processing is represented in a less regimented spatial format in mathematicians compared to those with lower mathematical expertise, such a task requiring only the semantic representation of number may be even less likely to generate a SNARC effect in professional mathematicians. Indeed, the use of a comparison task, where spatial representation of number is more effective for performance, would possibly uncover a SNARC effect in professional mathematicians (Cipora et al., 2015). However, this study provides some evidence for changes in the nature of symbolic numerical representations with increased mathematical experience, although contradicting the finding of increased SNARC effects with older age (Hoffmann et al., 2014; Wood et al., 2008), individuals suggested to possess enhanced and more automatic numerical experience due to lifespan exposure to numbers (Cappelletti et al., 2014; as in chapter 2: Norris et al., 2015; Uittenhove & Lemaire, 2015). However, reduced inhibitory control may contribute to increased SNARC effects in older age (Hasher & Zacks, 1988; Hoffmann et al., 2014). Indeed, a reduced SNARC effect in professional mathematicians (Cipora et al., 2015) may reflect enhanced inhibitory control and a more abstract numerical representation in such groups, rather than an effect of cumulatively increasing numerical experience.

5.1.3 Ageing, the approximate number system, and mathematical achievement

The effect of mathematical education on foundational numerical abilities in ageing is unclear. In the first study to investigate foundational numerical skills and mathematical ability in ageing, Cappelletti et al. (2014) measured non-symbolic numerical discrimination acuity and mathematical achievement in a group of younger and older adults. Using brief displays (200ms) of intermixed blue and yellow dot stimuli, participants decided which dot set was most numerous. Cappelletti et al. (2014) found impaired ANS acuity (higher w_s) for the older compared to the younger group, but further analyses suggested that this result was caused by poorer performance by older participants during incongruent trials only. The authors interpreted the findings to indicate that foundational numerical skills are maintained in ageing, but may appear to be declined in older age due to the effect of reduced inhibitory control (Hasher & Zacks, 1988). The neglect of such detailed investigation of congruency effects on performance was suggested by the authors to explain the findings of deteriorated ANS acuity in ageing found by Halberda et al. (2012), where only overall acuity was reported. Further, Cappelletti et al. (2014) found a relationship between non-symbolic discrimination acuity and older adults' performances on arithmetical problem verification, multi-digit arithmetic, and arithmetic problem solving, although these results were not compared with the relationship between such abilities in the younger group. It is unclear therefore whether the nature of a link between ANS acuity and mathematical achievement was affected by ageing. As results from a single-digit symbolic numerical comparison task were not elaborated or compared between age groups, foundational symbolic abilities in ageing were further investigated in chapter 2 (Norris et al., 2015). However, Cappelletti et al. (2014) suggest that the preservation of mathematical abilities, alongside preserved performance during congruent trials on the non-symbolic discrimination task indicate that numerical abilities as such are not impaired in ageing. Finally, the authors found no effect of years of formal education generally, or in mathematics specifically, on foundational non-symbolic numerical skills. The findings provide some indication that ANS acuity may be preserved in ageing when controlling for the effects of declined inhibitory control, and that education in mathematics does not appear to mediate ANS acuity in ageing (reflecting previous research with adults: Castronovo & Göbel, 2012; Inglis et al., 2011). However, the effect of an enhanced education in mathematics on numerical abilities in ageing is yet to be directly tested.

Chapter 2 sought to further investigate the effect of ageing on both foundational non-symbolic and symbolic numerical skills, and the relationship between such abilities and mathematical achievement. Non-symbolic abilities were found to be preserved in ageing, with enhanced symbolic abilities in the older group. Crucially, older adults achieved significantly higher scores for mathematical achievement, but such scores did not correlate with ANS acuity in either group. Better mathematical achievement was related to stronger foundational symbolic discrimination, but being older predicted enhanced foundational symbolic skills over and above higher mathematical achievement. This finding suggests that older adults' enhanced foundational symbolic ability appears to be primarily driven by being older, and therefore having more lifetime experience with numbers, rather than by superior mathematical skills. It may be predicted therefore that even further and more explicit experience with numbers achieved through a higher education in mathematics may *additionally* enhance symbolic numerical abilities in ageing. Moreover, investigation of older groups with a higher education in mathematics would uncover whether higher mathematical education affects foundational non-symbolic numerical abilities in ageing. Studies finding a relationship between ANS acuity and mathematical achievement would suggest improved ANS acuity with higher mathematical expertise in ageing (as in Guillaume et al., 2013). However, studies finding no link between mathematical achievement and ANS acuity for groups with higher mathematical education (Castronovo & Göbel, 2012) would suggest that ANS acuity remains stable in ageing regardless of mathematical education. The current study therefore constitutes the first to investigate how a further education in mathematics may affect foundational numerical skills in ageing. As older adults without further mathematical education have demonstrated enhanced foundational symbolic skills and preserved non-symbolic abilities, studying such abilities in an older group with a higher education in mathematics will assist in delineating which effects may be due to ageing and lifetime experience with and exposure to numbers, and which may be due to superior mathematical skills in the older generation (Geary & Lin, 1998). Therefore, should foundational numerical skills be preserved in ageing due to their primitive, evolutionary nature, it may be expected that further mathematical education will not affect such numerical skills in ageing. However, if non-symbolic abilities are related to mathematical achievement, older adults educated in degree-level mathematics may be able to show not only preserved, but superior ANS acuity compared to older adults without specific further education in mathematics, as well as superior symbolic numerical abilities.

5.1.4 The current study

Previous research has begun to investigate the effect of higher mathematical education on foundational numerical abilities. However, findings have been contradictory, reflecting the debate surrounding the link between ANS acuity and mathematical achievement in adults more generally. Whereas some have found increased precision of the ANS in groups with higher levels of mathematical education (Guillaume et al., 2013), others have found similar acuity regardless of mathematical expertise (Castronovo & Göbel, 2012). Moreover, whether ANS acuity and measures of mathematical achievement correlate in groups with higher mathematical education remains disputed (correlation: Guillaume et al., 2013; no correlation: Castronovo & Göbel, 2012). As recent evidence suggests altered symbolic numerical representations in groups with higher mathematical experience (e.g. absent SNARC effect: Cipora et al., 2015), alongside varying numerical abilities with increasing age (enhanced foundational symbolic skills in chapters 2 and 3: Norris et al., 2015; stronger

SNARC effect: Wood et al., 2008), further investigation is required into changes in numerical representations across the lifespan, specifically with regard to the impact of mathematical education. Firstly, the results from chapter 2 suggest that lifetime experience with numbers is primarily responsible for enhanced symbolic skills in older participants. Although regression analyses provided evidence for a stronger effect of ageing than higher mathematical achievement on enhanced symbolic acuity, mathematical achievement contributed to a significant proportion of the variance in symbolic acuity. Further investigation utilising a group with a higher mathematical education will help to uncover the contributions of ageing and mathematical achievement to enhanced symbolic abilities. Secondly, it could be suggested that foundational non-symbolic numerical skills are preserved in ageing due to their relationship with other numerical abilities (Cappelletti et al., 2014), and therefore higher mathematical education may present a further protective effect on ANS acuity in ageing. In order to directly address the question of the role of enhanced mathematical experience in ageing on foundational numerical abilities, the current study will compare a group of older adults with a degree in mathematics to a control group of older adults without higher mathematical education. Basic non-symbolic and symbolic numerical abilities will be compared between groups, as well as the relationship between these skills and mathematical achievement. As the results from chapters 2 and 3 suggest that ageing may result in a benefit from lifetime experience using numbers, it is expected that symbolic abilities may be enhanced in the maths alumni group beyond the performance of the control group. If the ANS is preserved in ageing due to its innate, primitive nature (Cappelletti et al., 2014; Dehaene, 2009; Norris et al., 2015), acuity should not be affected by a higher education in mathematics (as in Castronovo & Göbel, 2012), and should therefore be similar between groups. On the contrary, if ageing effects on foundational numerical abilities are driven by older adults' higher mathematical achievement (Geary & Lin, 1998), both non-symbolic and symbolic numerical abilities may be further enhanced in the alumni group.

5.2 Methods

5.2.1 Participants

11 participants aged 61-78 with an undergraduate degree in Mathematics were recruited via alumni relations at the University of Hull (9 males; M = 73, SD = 7). All alumni living within a 100 mile radius of the University of Hull who completed a degree in Mathematics were invited by email or post to participate (travel expenses were reimbursed). 27 potential participants responded to the invitation, but 16 could not participate for a variety of reasons (travel restrictions, etc). After screening, 11 participants were tested. 3 alumni participants were excluded from the analyses for scoring over 5 on the GDS. Therefore, data for 8 alumni were analysed. These participants had all at a minimum completed a BSc degree in Mathematics at the University of Hull. Although the exact the degree varied between participants, from special maths and pure and applied mathematics to mathematics and statistics, mathematics was the primary component in each case. The alumni cohort consisted of mostly retired older adults from a range of occupations, including three in consultancy/advisor roles, three teachers, and two working with system and software analysis and engineering. Data analysed for the control group are derived from the data reported in chapter 2 (26 older adults aged 60-77 (14 males; M= 65, SD= 4.5)). One participant's data was not recorded due to a computer error. As a result, a total of 25 older control participants' data were included in the current study. The control group ranged in education level, from no formal qualifications (1), to O levels (1), A levels (2), Diploma (1), Degree (BEd x2, BSc x2, BA x10), HNC (1), Master's Degree (MA x2, MSc x1), a DPhil, and a PhD. In terms of mathematical education, some participants in the control group had no formal qualifications in mathematics (5), whereas others achieved O Level (16) and A Level (4) mathematics. Finally, the control group's occupations ranged from no formal employment to academic.

5.2.2 Materials

The Mini Mental State Exam (MMSE: Folstein et al., 1975), Geriatric Depression Scale (GDS: Yesavage et al., 1982), WRAT4 spelling subtest (Castronovo & Göbel, 2012; Sasanguie et al., 2013), and the calculation task (Castronovo & Göbel, 2012) were administered (described in chapter 2, p.28). Additionally, the classic colour Stroop test measured inhibition in the alumni group (see chapter 3, p.58), as well as the Mathematics subsection of the WRAT4 as a further measure of mathematical achievement, with 40 mathematical problems presented in increasing difficulty, including divisions, fractions and financial questions (as in Castronovo & Göbel, 2012). Participants had 15 minutes to answer as many questions as possible. These additional measures were only administered to the alumni group as this group was tested at a later date, and data for the control participants was taken from previously collected data not using these additional control measures.

5.2.3 Non-symbolic comparison task

The task replicated that from chapter 2. Spatially separated sets of between 5 and 21 blue and yellow dots were displayed simultaneously for 200ms (as in Halberda et al., 2012). Participants chose the more numerous set using the 'F' and 'J' keys, which were coloured in blue and yellow dots respectively. The yellow dots appeared on the left, and the blue dots on the right. Trials were either congruent or incongruent. Once the participant pressed the space bar, stimuli appeared for 200ms, followed by a colour-matched backward mask (200ms). Then a prompt was displayed until an answer was recorded. Participants were asked to answer using their best impression and not to count. Accuracy, RTs, and the Weber fraction (w) were recorded. There were 384 trials, split into four ratio bins: 1.2, 1.3, 1.8, and 3, denoting the ratio between the blue and yellow dot sets. Analyses will investigate the effect of ratio, congruency, and mathematical education group on ANS acuity.

5.2.4 Symbolic comparison task

The task reflects that used in chapter 2. Stimuli comprised of a pair of two-digit numbers (e.g. 46 58) ranging from 21 to 98, presented simultaneously in black font on a white background (Nuerk et al., 2001). Participants decided whether the larger number (in magnitude) was on the left or right of the screen. Stimuli were of identical physical size. Numerical distances between stimuli pairs were grouped into four distance bins: 6- 15, 16-24, 25- 49, 51- 71. There were 16 practice trials with feedback, followed by 240 randomised trials presented in two blocks. A black fixation cross appeared on a white background for 1000ms, followed by the stimuli until response (maximum 3000ms). Participants responded as quickly and as accurately as possible using the keyboard (A= left, L= right). Analyses will investigate the effects of distance and participant group on accuracy and RTs.

5.2.5 Procedure

The study was a mixed design. Participants belonged to either the control or alumni group, and took part in the same tasks in a fully counterbalanced manner. However, the alumni group were additionally administered the colour Stroop and WRAT4 mathematical achievement tasks.

5.3 Results

Firstly, differences between the mathematics alumni group (henceforth 'alumni'), and the healthy older controls ('controls') on control measures (spelling and mathematical achievement) were investigated using independent *t*-tests. Mixed ANOVAs were then conducted to investigate the effect of group and ratio/distance on accuracy and RTs for the non-symbolic and symbolic comparison tasks, followed by ANOVAs on congruent and incongruent RTs, accuracy, and w_s in the non-symbolic comparison task to assess the impact of further mathematical experience in ageing on foundational numerical skills. Where sphericity was violated, Greenhouse-Geisser corrections apply. Finally, correlations were conducted to investigate the relationship between mathematical achievement and foundational numerical skills.

5.3.1 Non-symbolic comparison

ANOVAs were conducted to investigate the impact of group (alumni or control), numerosity ratio, and congruency (congruent or incongruent) on RTs, accuracy, and *w*. The alumni group's data were trimmed by applying a 3xSD cut-off for individual RTs (1.02% of data removed). Neither the alumni nor control group showed a speed-accuracy trade-off (p_s > .3). Firstly, ratio effects on RTs and accuracy were investigated for each group with a 4 (ratio bin) x 2 (group) mixed ANOVA, with ratio bin as a within-subjects factor, and group as a between-subjects factor. Ratio bin had a main effect on RTs, $F(1.63, 50.40) = 100.39$, $p < .001$, with decreasing RTs with increasing ratio reflecting the classic ratio effect (Dehaene, 1997; Piazza & Izard, 2009). There was no main effect of group ($p > .8$), and no group x ratio interaction ($p > .5$), suggesting similar overall response speed and ratio effects on RTs for both groups. For accuracy, there was a main effect of ratio, $F(1.95, 60.58) = 196.23$, $p < .001$, with more accurate responses with increasing ratio, demonstrating the classic ratio effect (Dehaene, 1997; Piazza & Izard, 2009). Reflecting RT analyses, there was no main effect of group and no group x ratio interaction on accuracy ($p_s > .3$), suggesting similar overall accuracy and ratio effects on accuracy between groups. These analyses suggest similar non-symbolic numerical abilities between the control and alumni groups.

Secondly, congruency and group effects on ANS acuity were investigated with 2 (congruency) x 2 (group) mixed ANOVAs on accuracy, *w*, and RTs. For accuracy, there was a main effect of congruency ($F(1, 31) = 10.27$, $p < .01$), with higher accuracy during congruent

(M = 91.13%, SD = 2.85) compared to incongruent trials (M = 90.52%, SD = 2.93) for all participants. There was no main effect of group (p > .3). However, there was an interaction between congruency and group (F(1, 31) = 5.37, p = .027), which appears to be due to a significant congruency effect in the control group, but similar performance on congruent and incongruent trials for the alumni group (see Figure 17). Paired t-tests per group indicate a significant difference between control participants' accuracy on congruent trials (M = 91%, SD = 3.1) compared to incongruent trials (M = 88%, SD = 4.3; t(24) = 5.472, p < .001). However, the difference between accuracy on congruent and incongruent trials did not reach significance for the alumni group (p > .5). Such results suggest a stronger congruency effect on accuracy for the control group, and an absent congruency effect for the alumni group. Analyses on w_s reflect those of accuracy, with a main effect of congruency due to higher w_s for incongruent (M = .203, SD = .060) compared to congruent trials (M = .162, SD = .039; F(1,31) = 8.57, p < .01), no main effect of group (p > .1), and an interaction between congruency and alumni (F(1,31) = 4.85, p < .05). An independent t test indicated a similar w during congruent trials between groups (p > .8), and a marginally higher w on incongruent trials for the control group (M = .215, SD = .063) compared to the alumni group (M = .167, SD = .036: t(31) = 2.026, p = .051). Moreover, separate paired t tests per group indicated similar w_s on congruent and incongruent trials for the alumni group (p > .6). However for the control group, w_s were significantly higher during incongruent trials (M = .215, SD = 063) compared to congruent trials (M = .163, SD = 042: t(24) = -4.930, p < .001). For RTs, responses were significantly faster for congruent (M = 913ms, SD = 360) compared to incongruent trials (M = 925ms, SD = 348: F(1, 31) = 5.34, p = .028). There was however no main effect of group (p > .9) and no group x congruency interaction (p > .7). Initially, it appears that ANS acuity is similar between groups. However, congruency analyses indicate that older adults without further mathematical education may be more negatively affected by incongruent dot size than older adults with a higher education in mathematics.

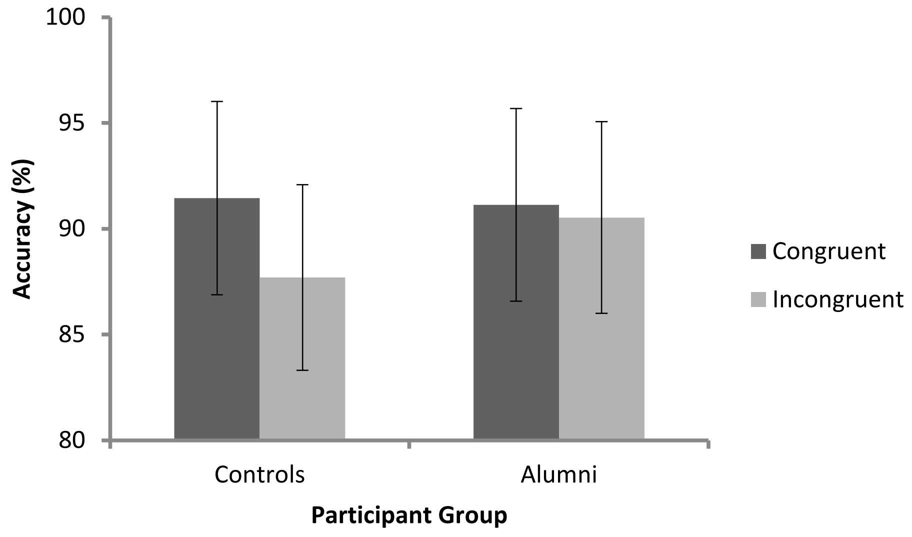

Figure 17: The congruency effect on non-symbolic accuracy for the control and alumni groups

5.3.2 Symbolic comparison

In order to investigate the impact of mathematical experience on basic symbolic numerical skills in ageing, analyses were conducted on RTs and accuracy for the symbolic comparison task. RT data for the alumni group were trimmed by applying the same 3 SD cut-off as in the non-symbolic comparison task (0.99% data removed). Neither group presented a speed-accuracy trade-off (p_s > .2). Firstly, effects of distance and group were investigated for accuracy and RTs with 4 (distance bin) x 2 (group) mixed ANOVAs, with distance bin as a within-subjects factor, and group as a between-subjects factor. For accuracy, there was a classic main effect of distance, higher accuracy with increasing distance (F(1.91,59.06) = 13.04, p < .001: Dehaene, 1997; Piazza & Izard, 2009). There was no main effect of group (p > .1), and no interaction (p > .4). For RTs, there was also a main effect of distance, with decreasing RTs with increasing distance (F(1.97,61.08) = 155.22, p < .001). There was however no main effect of group (p > .3), and no group x distance interaction (p > .9). Such results indicate similar symbolic discrimination and distance effects between groups.

5.3.3 Control measures and correlations

Group differences were marginally non-significant for age, education, spelling, and mathematical achievement (MA). Participants in the alumni group were slightly older (M = 70.9, SD = 7) than those in the control group (M = 65.4, SD = 5; t(9.004) = 2.134, p = .062).

The alumni group also had a slightly higher number of years in formal education (M = 18.3, SD = 2) compared to controls (M = 16.5, SD = 3: $t(31) = 1.769$, $p = .087$). For spelling, controls achieved slightly higher scores (M = 86.1%, SD = 9) than alumni (M = 79.8%, SD = 7; $t(31) = -1.919$, $p = .064$). Finally, the alumni group demonstrated slightly higher MA (M = 95.6%, SD = 4) than the control group (M = 90.6%, SD = 7; $t(31) = 1.941$, $p = .061$). It is emphasised however that in each case significance was marginal ($p_s > .05$).

Correlational analyses were conducted for all participants between ANS acuity, symbolic acuity, MA, and spelling, as well as WRAT4 mathematical achievement and colour Stroop interference in the alumni group. Results indicate that the correlation between MA and ANS marginally failed to reach significance (*w:* $r = -.322$, $p = .067$ and accuracy: $r = .305$, $p = .085$), indicating either no relationship or a weak relationship between mathematical achievement and ANS acuity in ageing. Further, there was no correlation between ANS acuity and the WRAT4 maths scores in the alumni group ($p > .1$). Separate correlations per group revealed that higher symbolic accuracy correlated with higher MA for the control group ($r = .641$, $p < .01$), but not for the alumni group ($p > .5$). However, the correlation between higher symbolic accuracy and WRAT4 mathematical achievement reached significance for the alumni group ($r = .765$, $p < .05$). Such results reflect a correlation between mathematical achievement and symbolic numerical abilities (e.g. De Smedt et al., 2013), and indicate that groups with higher mathematical education may require a more discriminative mathematical achievement measure to reveal such a relationship. Finally, lower interference scores on the colour Stroop task correlated with a higher WRAT4 math score in the alumni group ($r = -.781$, $p < .05$), reflecting a correlation between mathematical achievement and inhibition for the alumni group (Bull & Scerif, 2001; St Clair-Thompson & Gathercole, 2006).

5.4 Discussion

The current study aimed to further investigate the findings of chapters 2 and 3, where foundational non-symbolic abilities were found to be preserved, and symbolic abilities enhanced in ageing. The finding of superior symbolic abilities in ageing was concluded to result from longer lifetime experience with numbers, whereas stable ANS acuity in ageing was suggested to reflect the preservation of an innate, primitive numerosity system (Dehaene, 1997, 2009). The current chapter aimed to further investigate the potential effect of experience with numbers across the lifespan on foundational numerical abilities by comparing the results of the older adult group from chapter 2 with a group of older adults with a mathematics degree. Such participants were expected to benefit from additional lifetime experience with numbers due to their explicit education in mathematics (Castronovo & Göbel, 2012; Cipora et al., 2015; Guillaume et al., 2013). Therefore, whether this group's further experience with numbers (e.g. through exposure to digits, manipulation of numbers and mathematical concepts, etc) mediated the impact of ageing on foundational numerical abilities was directly investigated. The findings suggest that the effect of ageing on ANS acuity does not appear to be mediated by higher mathematical education, replicating previous findings of similar ANS acuity between groups with and without a higher education in mathematics (Castronovo & Göbel, 2012). Further, the control and alumni groups showed similar symbolic discrimination performance. Crucially, the control group showed a stronger congruency effect during the non-symbolic task (i.e. lower accuracy during incongruent compared to congruent trials), than the alumni group (e.g. Guillaume et al., 2013), possibly indicating stronger inhibitory control in older adults with a higher education in mathematics (Cipora et al., 2015). Overall, the current findings support similar foundational non-symbolic and symbolic numerical abilities in ageing, regardless of mathematical education. However, the results also demonstrate that groups with higher mathematical education may show an advantage during incongruent trials on an ANS task, potentially due to their enhanced inhibitory control (Cipora et al., 2015). However, this did not result in a group difference in overall acuity. It is unclear within the current findings whether there may be a group difference for inhibitory control, as an interference measure was only taken for the alumni group. However, the findings support the suggestion that foundational numerical abilities are preserved in ageing, and enhanced in the case of symbolic discrimination. Preserved foundational numerical abilities in ageing do not therefore appear to be driven by the superior mathematical ability of older adults

(Geary & Lin, 1998), as abilities were similar between groups. However, as the control group's symbolic accuracy was already high and near ceiling, it is likely that symbolic comparison tasks may suffer ceiling effects in some groups, such as older adults and mathematically educated participants.

Firstly, both groups showed similar performances in terms of overall accuracy, RTs and *w* on the non-symbolic discrimination task, with similar ratio effects on performance. Together, these findings suggest similar ANS acuity in older adults regardless of their level of education in mathematics (Castronovo & Göbel, 2012). However, those in the control group showed more interference from incongruent visual cues (dot size) compared to participants in the alumni group, with a congruency effect found for the control group only. A few potential explanations for this finding are discussed. Firstly, a smaller effect of dot size/area congruency on responses to numerosity in those with higher mathematical education reflect the findings of Guillaume et al. (2013), who suggested that individuals with superior mathematical experience may perceive the numerical cue as more salient than other visual cues, reducing the effect of incongruent dot size on performance. Further, as a response based on incongruent perceptual variables must be inhibited prior to processing numerosity during an incongruent trial (Clayton & Gilmore, 2014; Gilmore et al., 2013; Szűcs et al., 2013), and individuals with a degree in mathematics may have superior inhibition skills (Cipora et al., 2015), participants in this group may have been able to more effectively inhibit a response to dot size compared to the control group. Such a conclusion is supported by the finding that a congruency effect on RTs was found for all participants, whereas the congruency effect on accuracy and w_s was strongest in the control group. This supports the suggestion that the alumni were more able to overcome the negative effect of interference during an incongruent trial to produce a correct response. The findings suggest therefore that, when considering group differences caused by inhibitory control, ANS acuity appears to be similar between groups regardless of mathematical education. Such a finding emphasises the importance of assessing congruency effects directly when comparing ANS acuity across groups, as congruency effects may drive a difference in ANS acuity, particularly in older age (e.g. Cappelletti et al., 2014, 2015).

Symbolic discrimination acuity was similar between groups, with similar distance effects for the control and alumni participants. Comparable symbolic abilities between groups may be explained by the likelihood of ceiling effects: the control group already demonstrated superior performance on symbolic tasks compared to younger adults in chapters 2 and 3, with high overall accuracy scores (>90%). Although the alumni group scored around 95% accurate, it is possible that ceiling effects may have reduced the capacity to detect a group difference in the current study. The results therefore contradict those in previous literature of higher symbolic accuracy in high mathematically-educated young adults (Castronovo & Göbel, 2012; Guillaume et al., 2013). However, these studies were conducted with younger participants immediately post-degree. Therefore, the potential benefits of higher mathematical education on task performance may have been stronger than in the current study, where participants were tested decades after completing their degrees. The current findings suggest that high symbolic discrimination acuity in ageing as a result of lifetime experience with numbers may lead to similar symbolic skills between older groups with or without a higher mathematical education, possibly due to control groups 'catching up' with the foundational symbolic attainment of mathematically educated groups with the aid of lifetime exposure to numbers. This may also be supported by the straightforward and automatic nature of the task. That distance effects on accuracy and RTs were similar between groups further supports similar acuity of symbolic representation between groups. It is therefore likely that, as with ANS acuity (Castronovo & Göbel, 2012), foundational symbolic abilities may reach a maximum, particularly in older age.

Finally, the relationship between foundational numerical abilities and control measures, specifically mathematical achievement and inhibition in the alumni group, were investigated. MA was similar between groups, possibly as with the symbolic discrimination task due to high scores in the control group creating a ceiling effect. Crucially however, the correlation between ANS acuity and mathematical achievement failed to reach significance. This finding suggests that, even with further education in mathematics, mathematical achievement may not correlate with ANS acuity in ageing, reflecting the findings from chapter 2 (Norris et al., 2015). Such results also echo those in previous literature of the absence of a correlation between the ANS and mathematical achievement in participants with higher mathematical education (Castronovo & Göbel, 2012), further supporting the suggestion that mathematical achievement and ANS acuity may not correlate in adults (Inglis et al., 2011). However, this contradicts the findings of Guillaume et al. (2013), who not only found superior ANS acuity in high-mathematically educated participants, but also found a link between enhanced ANS acuity and higher mathematical achievement. A potential explanation for such a discrepancy may be that Guillaume et al. (2013) used congruent, incongruent and anticorrelated trials for their ANS measure, whereas congruent and incongruent trials only were used in the current study. The use of an additional set of incongruent trials may have increased the inhibitory load of Guillaume et al.'s (2013) ANS measure, possibly leading to a higher likelihood of achieving a correlation due to the link between mathematical ability and inhibitory control (Bull & Scerif, 2001; Clayton & Gilmore, 2014; Fuhs & McNeil, 2013; Gilmore et al., 2013). Indeed, superior performance on the WRAT4 mathematical achievement measure in the alumni group correlated with lower interference during the colour Stroop task, demonstrating the role of inhibitory control during mathematical processing even in a high-mathematically educated older group. Replicating previous findings, foundational symbolic abilities correlated with MA for the control group, but only with the more complex and discriminative WRAT4 mathematical achievement measure for the alumni group. This discrepancy between the groups further supports the notion of a ceiling effect on alumni participants' calculation scores, in that only performance on a more complex mathematical achievement measure correlated with symbolic acuity in this group. It is important to note here that sample sizes in the current study, particularly for the alumni group, were small. Therefore, caution must be exercised when interpreting the correlational analyses. It is imperative that future studies using larger staple sizes provide further evidence to support the preliminary correlational findings reported here.

In conclusion, ANS acuity does not appear to be affected by ageing, even when older participants have a higher education in mathematics. Explicit further experience with mathematics does not therefore appear to enhance, or to provide a 'protective' effect to foundational numerical abilities when compared to ageing without further mathematical education. Such a finding also provides evidence for a diminished link between the ANS and mathematical achievement in adults, in that ANS acuity may reach a maximum in adulthood (Castronovo & Göbel, 2012; Inglis et al., 2011), reducing the magnitude of a correlation with age. The findings provide some preliminary support to those of chapter 2, with the absence of a correlation between ANS acuity and higher mathematical education and achievement. However, this relationship requires further research with larger sample sizes. There is mixed evidence for the impact of education on cognitive decline in ageing (Ardila, Ostrosky-Solis, Rosselli, & Gómez, 2000; Christensen, 2001; Van Dijk, Van Gerven, Van Boxtel, Van der Elst, & Jolles, 2008), with some finding a protective effect of higher levels of education on the rate of cognitive decline, and others finding no such protective effect. Available studies provide evidence that foundational numerical abilities appear to be preserved in ageing due to their innate nature (Dehaene, 2009), along with their embedded early appearance (e.g. Izard et al., 2009; Lipton & Spelke, 2004; Xu & Spelke, 2000), and therefore that such abilities are unaffected by level of education. Further, similar symbolic discrimination acuity between groups suggests that enhanced symbolic abilities in ageing are likely due to lifetime exposure to numbers, rather than being due to an effect of mathematical education (Geary & Lin, 1998). However, the likelihood of ceiling effects during symbolic comparison tasks (Lonnemann et al., 2011) may demonstrate that the utility of such tasks in measuring and comparing foundational symbolic abilities between groups should be considered. Alternative methods of investigating basic symbolic numerical abilities may therefore prove useful in further investigating the nature of enhanced symbolic abilities in ageing (e.g. priming paradigms: see chapter 3; Dehaene et al., 1998; Koechlin et al., 1999). Due to their inherently imprecise nature, non-symbolic numerical abilities may be more discriminable between groups, although the measurement of such abilities faces its own methodological challenges (for a review, see Dietrich, Huber, & Nuerk, 2015 and chapters 5 and 6 for direct testing). Future research should aim to investigate foundational non-symbolic and symbolic numerical skills and their relationship with mathematical achievement in younger and older adults with backgrounds in other areas which may lead to stronger numerical and mathematical skills, such as for example Engineering, Physics, or Accountancy. Such studies would further investigate whether aside from explicit mathematical education, education in other numerical domains may impact upon basic numerical skills and their link with mathematical ability. Overall, the findings from the current study support the existence of a preserved foundational non-symbolic numerical system and an enhanced foundational symbolic system in ageing, reinforcing chapters 2 and 3. Most importantly, the current chapter directly addressed the question of whether the impact of ageing on basic numerical skills is mediated by older adults' superior mathematical skills (Cappelletti et al., 2014; Hedden & Gabrieli, 2004; Norris et al., 2015; Salthouse & Kersten, 1993), or differences in mathematical education (Geary & Lin, 1998).

6 Section 2: Investigating the reliable measurement of ANS acuity in ageing

The preceding chapters have found that foundational non-symbolic numerical abilities appear preserved and symbolic skills enhanced in ageing. However, as discussed in previous chapters, studies investigating ANS acuity in ageing have varied in their task designs. Firstly, some have used spatially intermixed dot displays during ANS tasks, whereas others have used separated dot displays. Secondly, dot-size congruency controls have varied, with some using incongruent trials and others using anticorrelated trials. How such variation may affect ANS acuity outcomes in ageing remains unclear. The following section aims to directly investigate to what extent the design of ANS acuity tasks in terms of the spatial location of dots on the screen (spatially separated or intermixed), and methods of size control (congruent, incongruent and anticorrelated) may affect the reliable measurement of ANS acuity, and crucially the comparison of abilities between age groups.

7 Chapter 5: ANS acuity in ageing as measured by separate and intermixed dot displays

7.1 Declaration

This chapter is published in a different form as a research article under review:

Norris, J. E., & Castronovo, J. (under review). Dot Display Affects Approximate Number System Acuity and Relationships with Mathematical Achievement and Inhibitory Control. *PLoS ONE*

7.2 Introduction

7.2.1 Contribution of the current chapter

ANS acuity was found in chapter 2 to be preserved in ageing, with similar accuracy and w_s between younger and older groups, even when investigating congruent and incongruent trials separately. The results contradicted those of Cappelletti et al. (2014), who found impaired ANS acuity (higher w_s) in the older compared to the younger group, with this impairment driven by poorer performance during incongruent trials for the older group. The authors concluded that foundational numerical abilities are preserved in ageing, but may appear to be deteriorated due to older adults' poorer performance on trials requiring inhibitory control (but see Cappelletti et al., 2015 for a later study finding similar congruency effects for younger and older adults). Older adults were suggested to be particularly affected by incongruent trials due to reduced inhibitory control (Cappelletti et al., 2014; Hasher & Zacks, 1988; Kramer et al., 1994). Methodological variation between the study reported in chapter 2 and that of Cappelletti et al. (2014) may provide some explanation for the contradictory findings. Whereas Cappelletti et al. (2014) used spatially intermixed blue and yellow dot displays during their ANS task, in chapter 2 we used spatially separated dot sets. It is possible that, due to apparently stronger congruency effects for the older adults when intermixed dot displays are used (Cappelletti et al., 2014), such task design may increase inhibitory load, intensifying congruency effects for the inhibition-declined older group. Therefore, the current study focuses on the reliable measurement of ANS acuity in ageing by directly investigating the impact of using intermixed or separated dot displays on ANS acuity, and how such effects may differ between younger and older participants. The chapter will additionally study how such methodological variation impacts the relationship between ANS acuity, mathematical achievement and inhibitory control in younger and older adults.

7.2.2 Measurement of the approximate number system

The acuity of the ANS is commonly measured with the Weber fraction (*w*: Halberda et al., 2008), accuracy and reaction times (e.g. Fuhs & McNeil, 2013), ratio effects (Smets et al., 2013), point of subjective equality (Tokita & Ishiguchi, 2013), or a mix of these measures (e.g. Castronovo & Göbel, 2012; Halberda et al., 2008; Szűcs et al., 2013). Each measure has been implicitly assumed to index the ANS (Inglis & Gilmore, 2014). However, when directly comparing the reliability of each measure, Inglis and Gilmore (2014) found accuracy to be a superior index of ANS acuity over *w*, with numerical ratio effects (NREs) cited as the least reliable measure. As well as measures indexing ANS acuity, experimental methods used to test the ANS have varied widely (for a review, see Dietrich et al., 2015). Comparison tasks are most frequently used to test the ANS, although alternatives such as change detection paradigms have been used to accommodate participant age (e.g. infants). Studies using these varying experimental designs are then directly compared in the literature to discuss the development of the ANS from early childhood through to late adulthood. Such task variation may present a problem when assessing the lifespan development of the number sense, as it is unclear whether changes reflect ANS acuity development or in fact reveal methodological differences (Gebuis & van der Smagt, 2011; Smets et al., 2013, but see Szűcs et al., 2013; Price et al., 2012). This suggestion is supported by research concluding that w_s calculated for performance on same/different, habituation, and comparison tasks are poorly correlated, with accuracy in comparison tasks highest for both children and adults (Gebuis & van der Smagt, 2011; Smets, Gebuis, Defever, & Reynvoet, 2014). It is clear that comparison tasks cannot practicably be used to measure ANS acuity in infants. However, for the majority of ANS acuity research beyond infant populations, inconsistencies in task type, stimulus display, number of trials (Lindskog, Winman, Juslin, & Poom, 2013), set size (Clayton & Gilmore, 2014), perceptual variable control, acuity measures (RTs, accuracy, NRE and *w*), and stimulus onset duration may lead to misrepresentation of ANS acuity (Inglis & Gilmore, 2013) and its links with other abilities such as mathematical achievement (Gilmore et al., 2011; Inglis & Gilmore, 2014; Price et al., 2012).

7.2.3 ANS acuity and mathematical achievement in ageing

In testing the relationship between mathematical achievement and the ANS in adults, the majority of studies finding significant correlations have used spatially intermixed dot displays in non-symbolic discrimination tasks (see Figure 14: DeWind & Brannon, 2012; Halberda et al., 2012; Lindskog et al., 2013; Lourenco et al., 2012; but see Agrillo, Piffer, & Adriano, 2013; Libertus, Odic, & Halberda, 2012) whereas those finding no correlation have most often used spatially separated (Gilmore et al., 2013; Haist, Wazny, Toomarian, & Adamo, 2015; Inglis et al., 2011; Lyons & Beilock, 2011; Newton et al., 2014) or sequentially presented displays (Castronovo & Göbel, 2012). Therefore, it appears that stimulus presentation differences may affect the presence or otherwise of a correlation between ANS acuity and mathematical achievement (Inglis & Gilmore, 2014; Price et al., 2012), potentially due to the varied inhibitory loads of the designs. Moreover, studies implementing either intermixed or separate dot displays have presented contradictory conclusions regarding the effect of ageing on ANS acuity. Those using intermixed displays have found impaired ANS acuity with age (Cappelletti et al., 2014; Halberda et al., 2012), possibly as a result of poorer performance on incongruent trials due to deteriorated inhibitory control (Cappelletti et al., 2014). However, in chapter 2 similar ANS acuity was found for younger and older adults when using a separated dot display, even for incongruent trials. Such findings therefore imply that the nature of tasks used in measuring ANS acuity in ageing may affect outcomes, making a conclusion as to whether the ANS is preserved in ageing unclear.

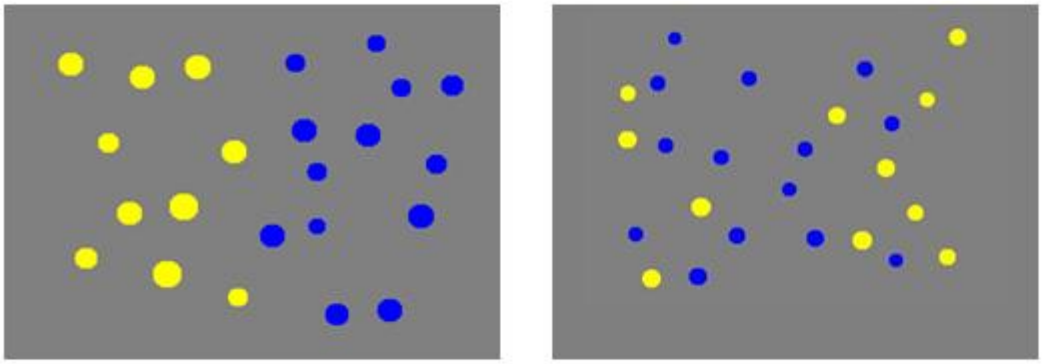

Figure 18: Examples of separate and intermixed dot displays during an ANS task (Halberda, Mazzocco, & Feigenson, 2008)

7.2.4 Inhibitory control during ANS tasks

An important factor currently under considerable debate is the contribution of inhibition to non-symbolic numerosity judgements. Dot size controls have been included to ensure that participants make judgements based on numerosity rather than other perceptual variables. Methods used to control perceptual variables have varied (Clayton & Gilmore, 2014; Smets et al., 2015), with most using congruent and incongruent trials. Such designs may present a Stroop-like effect (Abreu-Mendoza et al., 2013; Clayton & Gilmore, 2014; Fuhs & McNeil, 2013; Gilmore et al., 2013; Szűcs et al., 2013; but see Keller & Libertus, 2015), as during incongruent trials the irrelevant but salient and contradictory dimension (dot size) must be inhibited to judge the relevant dimension (numerosity). Some authors have concluded that ANS tasks may primarily measure inhibitory abilities, and that correlations between mathematical achievement and the ANS may predominantly reflect a relationship between inhibition and mathematical achievement rather than a correlation between ANS acuity and mathematical achievement (Clayton & Gilmore, 2014; Fuhs & McNeil, 2013; Gilmore et al., 2013). As a correlation between mathematical achievement and ANS acuity is most frequently found when intermixed dot displays are used, it is proposed that such task designs may have an increased inhibitory load, leading to a relationship between mathematical achievement and the inhibitory component of the ANS task. This conclusion may also be applied in interpreting the contradictory findings regarding the effect of ageing on ANS acuity. As older adults have impaired inhibitory control (Hasher & Zacks, 1988; Kramer et al., 1994), it may be expected that tasks with increased inhibitory load may affect ANS acuity in such groups more significantly than in younger groups with stronger inhibition skills.

7.2.5 The ANS in ageing

Although some suggest that numerical abilities deteriorate with age (Gandini et al., 2009; Halberda et al., 2012; Li et al., 2010; Trick et al., 1996), others, including chapter 2, suggest preserved numerical abilities in healthy ageing (Cappelletti et al., 2014; Lambrechts et al., 2013; Norris et al., 2015). Only three studies have attempted to directly measure the effect of ageing on ANS acuity. In their large-scale online study, Halberda et al. (2012) found that ANS acuity increases steadily throughout early development, peaking at around age 30. Their results suggest a steady increase in *w* (i.e. decreasing ANS acuity) after age 30, with the poorest ANS acuity observed in older age. However, Halberda et al.'s (2012) older adult sample was smaller than the other age groups, with participants aged over 60 showing significant individual variability in their responses, making the true trajectory of ANS acuity in ageing unclear. Crucially, the observed reduction in ANS acuity in older age was not further discussed by the authors, and the effect of congruent and incongruent trials was not investigated. In order to directly study the effect of ageing on the ANS, Cappelletti et al. (2014) tested a group of younger and older adults on a non-symbolic comparison task in which blue and yellow dots appeared intermixed on-screen for 200ms, and participants decided which set was most numerous. Cappelletti et al. (2014) found a decline in ANS acuity with ageing to be attributable to poorer performance during incongruent trials only where, due to reduced inhibitory control in ageing (Hasher & Zacks, 1988; Kramer et al., 1994), older adults were less able to inhibit the incongruent dot size to respond correctly to numerosity. The authors concluded that, due to the presence of preserved symbolic numerical abilities and arithmetical skills in the older group, poorer ANS acuity in the older group appears due to other processing requirements of the task (i.e. inhibitory control), rather than impoverished non-symbolic numerical skills in ageing (Cappelletti et al., 2014). In chapter 2, a group of younger and older participants completed an ANS task with the same size control methods as Cappelletti et al. (2014), but with 200ms displays of spatially *separated* blue and yellow dots. ANS acuity was similar between groups, with no specific deficit for the older group compared to the younger group during incongruent trials. Conflicting findings regarding dot-size congruency may be attributable to methodological differences between the studies, as Cappelletti et al. (2014) (as in Halberda et al., 2012) used intermixed dot stimuli, whereas we used separated dot displays (Gilmore et al., 2013; Inglis et al., 2011; Lyons & Beilock, 2011). It is possible therefore that both task designs create different demands on participants (e.g. overlapping dots during intermixed displays must be resolved before processing numerosity: Szűcs et al., 2013). Such differences may be particularly apparent in older groups, due to reduced inhibitory control (Cappelletti et al., 2014; Hasher & Zacks, 1988; Kramer et al., 1994), diminished useful field of view (Lemaire & Lecacheur, 2007), and slower eye movements in ageing (Spooner, Sakala, & Baloh, 1980; Warabi, Kase, & Kato, 1984). These factors, with the addition of reduced speed of processing in older age (Salthouse, 1996), may explain why resolving an intermixed dot display, whilst also inhibiting a response based on dot size during incongruent trials, and performing all of these steps quickly enough (within 200ms) to make a numerosity judgement may be more difficult for older adults. Such effects of ageing may therefore be responsible for seemingly poorer ANS acuity in older groups when intermixed displays are used (Cappelletti et al., 2014; Halberda et al., 2012), compared to similar ANS acuity between younger and older groups when using a separate display (chapter 2: Norris et al., 2015).

7.2.6 The current study

The current study aims to further investigate the effect of dot display (separate or intermixed) on ANS acuity in ageing. The link between ANS acuity (accuracy, *w*, and RTs), inhibition, and mathematical achievement in younger and older groups will also be investigated. The study will examine ANS acuity during congruent and incongruent trials derived from intermixed or separate dot displays, and how such factors influence the relationships between ANS acuity, inhibitory control and mathematical achievement in ageing. Inhibition will be measured to examine the contribution of inhibitory control to ANS task performance using a colour Stroop (Stroop, 1935) and a number Stroop task (Cohen Kadosh et al., 2008). Firstly, it is predicted that intermixed displays will result in poorer ANS acuity (higher w_s, lower accuracy and slower RTs) for all participants due to the extra step required in resolving the overlapping dot arrays (Szűcs et al., 2013). Secondly, it is predicted that reduced ANS acuity in the intermixed condition will be more apparent in the older compared to the younger group due to impaired inhibitory control in ageing (Cappelletti et al., 2014; Christensen, 2001; Hasher & Zacks, 1988; Kramer et al., 1994). Finally, as mathematical achievement and inhibition are frequently found to correlate (Clayton & Gilmore, 2014), a relationship between mathematical achievement and ANS acuity is expected to be primarily evident in the intermixed condition due to the increased inhibitory load of the task.

7.3 Method

7.3.1 Participants

Ninety-eight participants were recruited: 34 older adults aged 61-74 (14 males; M = 67yrs, SD= 3.7) and 64 younger adults aged 18-25 (15 males; M = 20, SD = 1.6)[ii]. 3 younger participants were excluded from the analyses for failing to complete the non-symbolic comparison task, 2 younger participants' data were excluded due to w_s > 4SDs from the group mean (as in Halberda et al., 2012), 2 younger participants and 1 older participant were excluded due to GDS scores >5, and 2 older adults were excluded due to MMSE scores <27. Therefore, a total of 88 participants' data was analysed.

7.3.2 Measures

The Geriatric Depression Scale (GDS: Yesavage et al., 1982), Mini-Mental State Exam (MMSE: Folstein et al., 1975), WRAT4 spelling subtest (Wilkinson & Robertson, 2006), calculation task, (see chapter 2, p.28), and the colour and number Stroop paradigms (see chapter 3, p.58) were administered.

Approximate Number System: The Panamath task was used to measure foundational non-symbolic numerical processing, with three measures (accuracy, RTs and *w*). Participants were asked to decide as quickly but as accurately as possible whether they had seen more blue or yellow dots (displayed for 200ms). Each trial began with the participant pressing the space bar. In the intermixed dot display condition, blue and yellow dots (between 5 and 21 per array) appeared in intermixed windows (size 100; see Panamath software: Halberda et al., 2008) on a grey background. During the separate dot display condition, blue dots appeared on the right and the yellow dots on the left of the screen in window sizes 45 (as in chapter 2). Participants chose the most numerous dot set using the 'A' (yellow) and 'L' (blue) keys covered with correspondingly coloured dots. Trials were either congruent or incongruent. There were eight trial types (2 x size congruency, 4 x ratio: 1.1, 1.19, 1.32, 2.28), with 400 trials total.

7.3.3 Procedure

The study used a mixed design. Participants took part in all tasks in a fully counterbalanced manner. For the Panamath task participants were randomly allocated to either a separated or an intermixed dot display condition. Participants completed either the physical or magnitude number Stroop task at the beginning of the session in a counterbalanced manner to avoid carry over effects. Panamath ran from Java, and the number Stroop tasks ran from E Prime 2.

7.4 Results

Data from the ANS task were trimmed by applying a 3 SD cut-off for individual RTs (1.81% of data removed). Accuracy, Weber fractions (*w*) and reaction times (RTs) on the ANS task are discussed in terms of congruent and incongruent trials (as in Cappelletti et al., 2014; Gilmore et al., 2013). Mixed ANOVAs were conducted for *w*, accuracy and RTs, with age group (young or older) and dot display (separate or intermixed) as between-subjects factors, and congruency (congruent or incongruent) as a within-subjects factor. Correlations were then investigated for each age group between ANS acuity, inhibition and mathematical achievement.

7.4.1 Weber fractions

A 2 (age group) x 2 (dot display) x 2 (congruency) mixed ANOVA was conducted on Weber fractions (*w*). *W*s were lower (superior ANS acuity) during congruent (M = .208, SD = 0.06) compared to incongruent trials (M = .276, SDs = 0.09; $F(1,84) = 96.16$, $p < .001$). There was a main effect of dot display, $F(1,84) = 53.72$, $p < .001$, with smaller w_s in the separate (M = .196, SD = 0.04) compared to the mixed condition (M = .287, SD = 0.07). There was no main effect of age group ($p > .7$), with older and younger adults presenting similar w_s overall: (older M = .242, SD = 0.06, younger M = .240, SD = 0.08), reflecting chapter 2 (Norris et al., 2015). The congruency x dot display interaction was marginally significant ($F(1,84) = 3.710$, $p = .057$), with separate ANOVAs revealing a tendency for a stronger congruency effect in the mixed (congruent M = 0.25, SD = 0.06; incongruent M = 0.32, SD = 0.08: $F(1,41) = 62.13$, $p < .001$) compared to the separate condition (congruent M = 0.17, SD = 0.04; incongruent M = 0.23, SD = 0.06: $F(1,43) = 34.48$, $p < .001$). Further, the interaction between congruency, age group and dot display reached significance ($F(1,84) = 4.28$, $p = .042$). Investigation of the congruency x dot display interaction separately for older and younger adults suggests that the interaction remains significant in the older group ($F(1,28) = 9.405$, $p = .005$), but not for the younger group ($p > .9$), indicating a tendency for a stronger congruency effect in the older group during intermixed displays (congruent M = 0.25, SD = 0.07; incongruent M = 0.35, SD = 0.08: $F(1,13) = 59.36$, $p < .001$) compared to separate displays (congruent M = 0.17, SD = 0.05; incongruent M = 0.21, SD = 0.07: $F(1,15) = 13.55$, $p < .01$). These results suggest that ANS acuity is overall similar between age groups, reflecting the findings from chapter 2. However, the results also demonstrate that older adults are more sensitive to the congruency effect during an ANS task, particularly when dots are displayed intermixed (see Figure 19).

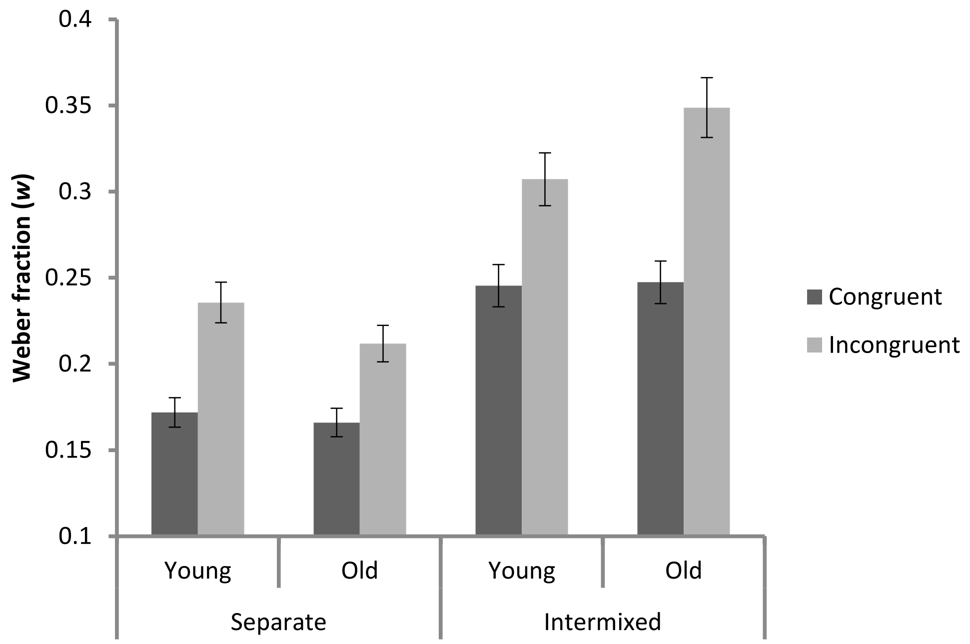

Figure 19: Weber fractions (w) derived from younger and older adults' performances on congruent and incongruent trials during the separate or intermixed condition

7.4.2 Accuracy

A 2 (age group) x 2 (dot display) x 2 (congruency) mixed ANOVA was conducted on accuracy. Reflecting analyses on w_s, accuracy was higher during congruent (M = 83%, SD = 3.8) compared to incongruent trials (M = 78%, SD = 4.1; $F(1,84) = 80.97$, $p < .001$). Accuracy was also higher in the separate (M = 84%, SD = 3.7) compared to the mixed condition (M = 77%, SD = 4.2; $F(1,84) = 55.86$, $p < .001$). There was no main effect of age group ($p > .8$; younger M = 80%, SD = 4, older M = 81%, SD = 3.9). However, there was a marginally significant interaction between age group and dot display ($F(1,84) = 3.010$, $p = .086$), and a marginally non-significant interaction between congruency, age group and dot display ($F(1,84) = 3.56$, $p = .063$). Separate ANOVAs for the younger and older groups with dot display as a between-subjects factor and congruency as a within-subjects factor indicate that the interaction between congruency and dot display remains marginally significant for the older group ($F(1,28) = 3.256$, $p = .082$), but not for the younger group ($p > .3$), due to a tendency for a stronger congruency effect during intermixed displays (congruent M = 80%, SD = 4.0; incongruent M = 74%, SD = 4.4) compared to separate displays (congruent M =

86%, SD = 3.5; incongruent M = 83%, SD = 3.8) for the older group (as with w_s). These results suggest that all participants were less accurate during incongruent trials, and less accurate during intermixed displays. However, although overall accuracy was similar between groups, the older group demonstrate a tendency for lower accuracy compared to the younger group during intermixed displays, particularly on incongruent trials (see Figure 20).

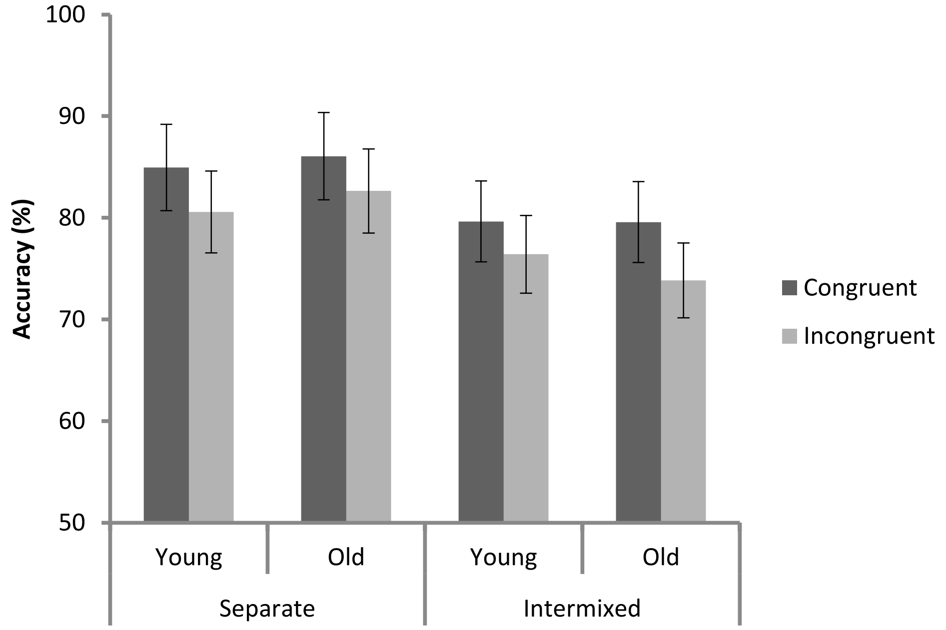

Figure 20: Younger and older adults' accuracy scores for congruent and incongruent trials during the separate or intermixed condition

7.4.3 RTs

A 2 (age group) x 2 (dot display) x 2 (congruency) mixed ANOVA was conducted for RTs on correct trials. There was a significant main effect of congruency, $F(1,84) = 96.53$, $p < .001$, with slower RTs on incongruent trials (M = 953ms, SD = 432) than congruent trials (M = 914ms, SD = 407). Responses were significantly faster in the separate (M = 850ms, SD = 359) than the intermixed condition (M = 1027ms, SD = 462; $F(1,84) = 35.89$, $p < .001$). Older adults were slower overall (M = 1073ms, SD = 530) than younger adults (M = 861ms, SD = 326; $F(1,84) = 40.21$, $p < .001$). Furthermore, there was a marginally non-significant interaction between congruency and dot display, $F(1,84) = 3.93$, $p = .051$, indicating a more pronounced difference between RTs on congruent and incongruent trials in the mixed (congruent M = 1005ms, SD = 448; incongruent M = 1050ms, SD = 475) compared to the separate condition (congruent M = 833ms, SD = 348; incongruent M = 868ms, SD = 369). An interaction between age group and congruency ($F(1,84) = 12.40$, $p = .001$) was further investigated with separate ANOVAs, which indicated that incongruent trials had a more detrimental effect on older (congruent M = 1044ms, SD = 515; incongruent M = 1103ms, SD = 544: $F(1,29) = 44.14$, $p < .001$) compared to younger adults' RTs (congruent M = 847ms, SD = 317; incongruent M = 875ms, SD = 335: $F(1,57) = 36.50$, $p < .001$). Moreover, there was a significant interaction between age group and dot display ($F(1,84) = 8.00$, $p = .006$), due to slower responses in intermixed compared to separate conditions in the older group (separate M = 932ms, SD = 419; intermixed M = 1249ms, SD = 598) than the younger group (separate M = 804ms, SD = 310; intermixed M = 921ms, SD = 331). These results demonstrate a particular weakness in the older group in processing intermixed trials, particularly when dot size is incongruent to numerosity (see Figure 21).

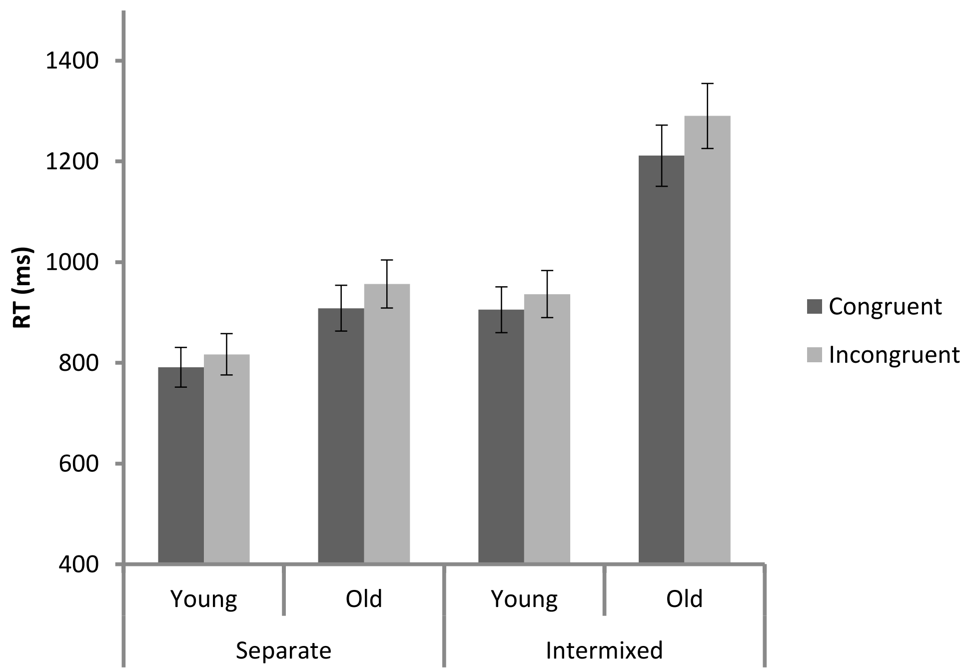

Figure 21: Younger and older adults' RTs on congruent and incongruent trials during the separate or intermixed condition

7.4.4 Control measures

An interference effect (RT on incongruent – RT on neutral trials) was calculated for the magnitude number Stroop task. Independent-samples *t*-tests were conducted to investigate group differences in years of education, spelling scores, mathematical achievement (MA), and interference effects on the colour and number Stroop tasks. There was no group difference for education ($p > .2$). The older group presented higher spelling scores (M= 83.25%, SD = 10.53) than the younger group (M = 73.97%, SD = 8.56; $t(86) = -4.45$, $p < .001$), reflecting preserved vocabulary in ageing (Cappelletti et al., 2014; Christensen, 2001; Watson et al., 2005). The older group also scored higher on MA (M = 87.09%, SD = 8.13) than the younger group (M = 70.11%, SD = 11.47; $t(77.60) = -8.02$, $p < .001$), as in previous chapters. Preserved or enhanced arithmetical ability in ageing has also been found in similar research (Cappelletti et al., 2014; Salthouse & Kersten, 1993). Interference effects were stronger for older adults in both the colour Stroop (older M = 16ms, SD = 5, younger M = 9ms, SD = 4; $t(86) = -7.065$, $p < .001$) and number Stroop tasks (older M = 52ms, SD = 28, younger M = 36ms, SD = 35; $t(86) = -2.169$, $p = .033$), reflecting reduced inhibitory control in ageing (Hasher & Zacks, 1988; Kramer et al., 1994).

7.4.5 Correlations between ANS acuity, mathematical achievement and inhibition

Correlations between MA, inhibition and ANS acuity were conducted for the older and younger groups separately for intermixed and separate conditions. Firstly for the younger adults during *separate* conditions, MA did not correlate with ANS acuity measures ($p_s > .2$). There was a significant correlation between number Stroop interference and the difference in RT between congruent and incongruent ANS trials (henceforth 'RT difference': $r = -.496$, $p = .006$), reflecting a relationship between interference effects for the Stroop and ANS tasks. The correlation between higher accuracy on congruent trials and lower interference effects approached significance ($r = -.334$, $p = .077$). These results demonstrate Stroop-like behaviour during an ANS task, as interference effects during the ANS and number Stroop task correlate. For younger participants in the *intermixed* condition, lower interference on the number Stroop task correlated with several ANS acuity measures (higher accuracy and lower w during congruent trials: $r = .407$, $p = .028$ and $r = -.396$, $p = .034$ respectively; slower RTs on incongruent trials: $r = .401$, $p = .031$, and a smaller RT difference: $r = .604$, $p <$

.01). These results suggest a stronger contribution of inhibitory control during an intermixed compared to a separate ANS task for the younger group. Further, a smaller accuracy difference (the difference between accuracy on congruent and incongruent trials) significantly correlated with higher MA scores (r = -.558, p = .002), as did accuracy on incongruent trials (r = .407, p = .028), with the correlation between higher MA and lower incongruent w approaching significance (r = -.337, p = .074). Together, these results suggest that MA correlates with ANS acuity measures in the younger group for those in the intermixed condition only. Further, the results demonstrate that higher MA correlates with a participants' ability to perform more accurately during incongruent trials on an intermixed task, indicating a link between higher MA and stronger inhibitory control during incongruent, intermixed ANS trials (e.g. Fuhs & McNeil, 2013; Gilmore et al., 2013).

For the older group, during *separate* displays there was a relationship between RT difference and age (r = .578, p = .019), indicating that inhibitory load during an ANS task intensifies with increasing age, whereby inhibitory control continues to decline (Cappelletti et al., 2014; Christensen, 2001; Hasher & Zacks, 1988; Hedden & Gabrieli, 2004; Kramer et al., 1994). For older adults in the *intermixed* condition, increasing age correlated with a larger accuracy difference (r = .575, p = .031), again reflecting the impact of reduced inhibitory control in ageing on accuracy performance during an intermixed ANS task. Therefore, although correlational analyses in the older group indicate that inhibition requirements during the separate dot display ANS task may lead to increased RTs, inhibitory load during the intermixed condition appears to affect ANS acuity in terms of accuracy, which is more often used as a primary index of ANS acuity, and is frequently compared between groups. It is possible therefore that due to declined inhibitory control with increasing older age, accuracy on an ANS task may decline with greater inhibitory load (when dots are intermixed).

7.5 Discussion

In the current study, the effect of stimulus display on ANS acuity in ageing was investigated, with younger and older participants completing a non-symbolic numerosity discrimination task using either intermixed or separate dot displays. The focus of the study was on determining how such methodological differences may affect ANS acuity in ageing, and its link with mathematical achievement and inhibition. As hypothesised, for all participants intermixed dot displays resulted in poorer ANS acuity than separate displays, contradicting the findings of Price et al. (2012) who found stable ANS acuity across intermixed, separate and sequential displays. Our study differs from Price et al. (2012) in crucial ways which may explain the contradictory findings. Firstly, we used a between-subjects design to reduce practice effects, whereas Price et al. (2012) used a within-subjects design. Second, we used a 200ms display (as in Halberda et al., 2008) to ensure only approximate abilities, and not counting, were measured. Price and colleagues' (2012) 750ms display may have encouraged counting and other strategies, possibly facilitating performance by providing more time for the successful resolution of overlapping dot arrays. This may have therefore masked ANS acuity differences between dot displays. Finally, we measured three indices of ANS acuity (w, accuracy and RTs for congruent and incongruent trials), whereas Price et al. (2012) only calculated w and NREs, the latter of which has been found to be an unreliable measure of ANS acuity (Inglis & Gilmore, 2014). The current study therefore builds upon research investigating the effect of task design on ANS measurement, using shorter display times to ensure that approximate abilities are measured, and additionally comparing such effects in younger and older adults. The current study addresses contradictory findings regarding ANS acuity in ageing by investigating whether methodological variation in terms of dot display may contribute to different findings in the literature (lower overall w in younger compared to older adults: Cappelletti et al., 2014; Halberda et al., 2012; and similar w_s between age groups: Norris et al., 2015).

The current study demonstrates that whether a separate or intermixed dot display is used in an ANS task affects acuity (accuracy, RTs, and w) for all participants. Reflecting the results from chapter 2, younger and older adults had similar ANS acuity in terms of accuracy and w, and older adults were slower overall, likely due to reduced speed of processing in ageing (Cappelletti et al., 2014; Salthouse, 1996). However, older adults appear to be particularly sensitive to intermixed dot displays, especially during incongruent trials. Indeed, speed of response in the older group was significantly slower during the intermixed compared to the separate condition, and older adults' ANS acuity was more negatively affected by incongruent trials during an intermixed display than younger adults', although this effect did not result in a group difference in overall ANS acuity (w_s and accuracy). These findings are supported by correlational analyses, which demonstrate in the younger group increased inhibitory load during the intermixed compared to the separate condition. A link between increasing age and stronger interference effects during the ANS task for the older adults provides further evidence that reduced inhibitory control in ageing may indeed affect ANS acuity due to poorer performance on incongruent trials (as in Cappelletti et al., 2014), particularly when dots are intermixed. The results from the current study therefore provide some explanation as to the contradictory findings of our first study and Cappelletti et al. (2014). The results suggest that, where spatially separated dot displays are used, younger and older adults have similar ANS acuity (i.e. the ANS is preserved in ageing, as in chapter 2). However, when spatially intermixed dot displays are used, ANS acuity can appear to be declined in older age (Cappelletti et al., 2014; Halberda et al., 2012). It seems likely that this decline is driven by older adults' poorer performance during incongruent trials as a result of their reduced inhibitory control (Cappelletti et al., 2014), particularly whereby dots are intermixed. It remains unclear whether such an effect could be present in the results of Halberda et al.'s (2012) large online study using intermixed displays, where ANS acuity was concluded to decline in ageing. It appears therefore that using a spatially intermixed display may increase task difficulty, particularly during incongruent trials and particularly in older age. In addition to reduced inhibitory control in older age (Cappelletti et al., 2014; Hasher & Zacks, 1988; Kramer et al., 1994), other biological and cognitive changes in ageing may impair older adults' performances on an intermixed ANS task. Older adults must inhibit a response based on dot size during incongruent trials, resolve the overlapping displays, and make a numerosity judgement, performing all of these steps in around the time stimuli are on-screen (200ms). A diminished useful field of view (Lemaire & Lecacheur, 2007), slower eye movements (Spooner et al., 1980; Warabi et al., 1984), and reduced processing speed in older age (Salthouse, 1996) may further contribute to a particular deficit in this group when resolving an intermixed dot display. The findings therefore emphasise the importance of task design in measuring ANS acuity, particularly in older groups.

An ongoing debate in the current literature remains the nature of a relationship between ANS acuity and mathematical achievement (MA). For the younger group, such a relationship was significant for participants in the intermixed condition only. This reflects previous findings (e.g. Halberda et al., 2012; Lourenco et al., 2012), and although the cause of this relationship is currently unknown, it may be attributable to greater inhibitory load during an intermixed task due to increased visual cues (Szűcs et al., 2013). Indeed, interference effects were related to younger adults' ANS acuity, particularly during the intermixed condition. The results from the current study therefore support the suggestion that where a link between ANS acuity and MA is found, such a relationship may indeed reflect a correlation between MA and the inhibitory load of an ANS task (Clayton & Gilmore, 2014; Fuhs & McNeil, 2013; Gilmore et al., 2013). These findings provide further evidence that dot display not only significantly affects ANS acuity measures, but also whether such measures correlate with MA (Inglis & Gilmore, 2013, 2014) seemingly due to variance in the inhibitory requirement of each design. These parameters must therefore be considered seriously when measuring the ANS and its relationship with other cognitive abilities, particularly mathematical achievement (Gilmore et al., 2011; Inglis & Gilmore, 2014; Szűcs et al., 2013). That a correlation between MA, interference, and ANS acuity measures was not found for older participants may be due to the smaller sample size of the older group, or due to older adults' higher and less varied MA scores. Future research would benefit from a larger overall sample size.

This study is the first to directly compare the use of intermixed and separate dot displays on ANS acuity in younger and older participants, and the effect of task design on the relationships between the ANS, inhibition and MA. The results reveal significant effects of dot display on the measurement of ANS acuity, posing important questions for the reliable and valid measurement of the ANS, particularly in groups with reduced inhibitory control such as older adults. The findings have implications for future research, in that ANS tasks using separated dot displays may be more reliable in directly measuring ANS acuity, rather than inhibitory control, particularly in ageing. Further, the results support previous findings of a link between ANS acuity and MA in adults during intermixed dot displays (e.g. Halberda et al., 2012), whilst such a link is less frequently found for separate displays (Gilmore et al., 2013; Inglis et al., 2011; Lyons & Beilock, 2011). Future studies employing detailed investigation of the effects of using different dot size controls (congruent, incongruent and/or anticorrelated) also requires further investigation, as anticorrelated trials may constitute another factor increasing the inhibitory load of the ANS task. The current findings however provide the groundwork for future research into the effect of dot display on the ANS in ageing, and demonstrate its importance in terms of the relationship between ANS acuity and MA, inhibition, and other cognitive abilities.

8 Chapter 6: Investigating the effect of dot size congruency on ANS acuity in ageing

8.1 Introduction

8.1.1 Contribution of the current chapter

The current chapter aims to further investigate methodological variation in measuring the ANS and how such disparity between studies may affect ANS acuity, particularly in older adults. The previous chapter identified issues with using intermixed vs. separate non-symbolic numerosity displays, and how inconsistent use of both designs throughout the literature may particularly impact ANS acuity outcomes in older participants due to their poorer inhibitory control. Indeed, older participants were found to be particularly negatively affected by intermixed dot displays, with poorer ANS acuity and higher individual variability. In the current chapter, another source of variation in ANS task design will be investigated, namely the way in which non-symbolic numerosity displays are controlled for the effects of dot size.

8.1.2 Varying methods of dot-size control

In making a judgement on the relative numerosity of two sets of dots during a non-symbolic comparison task, participants have been shown to be influenced by other perceptual variables including convex hull (i.e. the perimeter around a dot set: Clayton & Gilmore, 2014; Gebuis & Reynvoet, 2012c), and most notably dot size and total cumulative area of each dot set (Gebuis & Reynvoet, 2012a, 2012b, 2012c; Leibovich & Henik, 2013; Szűcs et al., 2013; but see Halberda et al., 2008). It is suggested that when the total cumulative area of each dot set is not controlled, i.e. where the more numerous set also has the largest total cumulative area and therefore a larger average dot size, participants are able to make judgements about quantity based on perceptual variables alone (e.g. larger blue dots), without engaging directly in a numerosity judgement. In order to address such concerns, researchers have used a variety of methods to control for the possibility of participants using dot size and cumulative area during ANS tasks (Abreu-Mendoza et al., 2013; Leibovich & Henik, 2013): congruent, incongruent and anticorrelated trials. However, which of these controls have been used has varied between studies (Abreu-Mendoza et al., 2013). Although most tend to combine congruent and incongruent trials, which of the incongruent and anticorrelated conditions have been applied as incongruent trials has varied. Whilst some have used congruent and incongruent trials (Cappelletti et al., 2014), others have compared congruent and anticorrelated trials (Gilmore et al., 2013; Hurewitz et al., 2006; Inglis & Gilmore, 2014; Odic, Libertus, Feigenson, & Halberda, 2013; Szűcs et al., 2013), with others using all three control conditions (DeWind & Brannon, 2012; Fuhs & McNeil, 2013; Keller & Libertus, 2015; Rousselle & Noël, 2008) or incongruent trials alone (Gray & Reeve, 2014). Although incongruent trial type (incongruent vs. anticorrelated) has varied, the effect of such variation has yet to be investigated.

As both incongruent (e.g. Cappelletti et al., 2014) and anticorrelated trials have been labelled throughout the literature as ‘incongruent’ (Gilmore et al., 2013; Szűcs et al., 2013), such variation in size-control methods, along with other task inconsistencies such as stimulus onset duration, separate vs. intermixed dots, number of trials, and numerosity ratio (Clayton & Gilmore, 2014; Inglis & Gilmore, 2013, 2014) may lead to an unclear picture of ANS acuity, particularly when comparing results from multiple studies (Szűcs et al., 2013). As incongruent trials may present a Stroop-like effect (Abreu-Mendoza et al., 2013; Szűcs et al., 2013; but see Keller & Libertus, 2015), it is currently unclear whether anticorrelated trials may produce a stronger Stroop-like effect compared to incongruent trials. This may be the case due to anticorrelated trials being ‘more incongruent’ than incongruent trials as cumulative area *negatively* correlates with numerosity (Fuhs & McNeil, 2013; Keller & Libertus, 2015), possibly leading to poorer ANS acuity. Therefore, the use of congruent and anticorrelated trials within the same paradigm, as opposed to congruent and incongruent trials, may lead to a steeper congruency effect on performance. This may create stronger congruency effects in studies using anticorrelated trials compared to those using incongruent trials, potentially undermining the measurement of the ANS itself and affecting the reliability of its link with other cognitive abilities, such an inhibition and mathematical achievement. On the other hand, incongruent and anticorrelated trials may present similar ‘Stroop effects’ due to both trial types not being ‘congruent’. Therefore, it would be expected that performance between incongruent and anticorrelated trials would be similar.

8.1.3 Inhibitory control during ANS tasks

A requirement for inhibitory control during ANS tasks has been suggested to account for correlations between ANS acuity and mathematical achievement (Clayton & Gilmore, 2014; Fuhs & McNeil, 2013; Szűcs et al., 2013; but see Keller & Libertus, 2015), as inhibition and mathematical ability are frequently correlated, particularly in children (St Clair-Thompson & Gathercole, 2006). However, the suggestion that inhibition processes are at play during ANS tasks remains subject to much debate. A recent study by Keller and Libertus (2015) directly tested the effect of inhibitory control on the relationship between mathematical achievement and ANS acuity in children aged 4-6. The authors concluded that, even when controlling for inhibition, the correlation between ANS acuity and mathematical achievement remained (Keller & Libertus, 2015), contradicting previous findings (Fuhs & McNeil, 2013; Gilmore et al., 2013). However, the experiments compared by Keller and Libertus (2015) utilised different levels of size control (congruent, incongruent, and anticorrelated in experiment 1, congruent and incongruent only in experiment 2). Such mixed use of size control methods, particularly if anticorrelated trials require a greater contribution of inhibitory control, could complicate the reliable analysis of the role of inhibition in ANS tasks. Therefore, although debate continues as to whether ANS tasks reliably measure numerical abilities, and to what extent they may measure inhibitory control, it remains unclear how variation in the levels of size control used between studies may mediate the inhibitory load of the task. This question is of particular importance considering the possibility that anticorrelated trials may produce a stronger requirement for inhibitory control compared to incongruent trials, and as a result may account for correlations between mathematical ability and ANS acuity (e.g. Fuhs & McNeil, 2013; Gilmore et al., 2013). In ageing, such variation may lead to differences in the degree of inhibitory load during an ANS task due to reduced inhibitory control in older age. As well as the impact of dot-size congruency on numerosity judgements, more recently the effect of the convex hull of dot displays on numerosity processing has been emphasised as an important influence on numerosity judgements (e.g. Clayton & Gilmore, 2014; Gebuis & Reynvoet, 2012c). The convex hull refers to the perimeter around a dot set. Convex hull may affect the processing of numerosity over and above dot size, particularly with larger numerosities (Clayton & Gilmore, 2014), even when convex hull does not predict numerosity (Gebuis & Reynvoet, 2012c). Therefore, alongside the investigation of size-control methods and their effect on ANS acuity, the impact of convex hull also constitutes an important consideration in analysing the role of perceptual variable congruency in ANS acuity in ageing.

8.1.4 Visual cues

In order to further investigate the effect of perceptual variables on numerosity tasks, some researchers have directly measured participants' area discrimination skills (Hurewitz et al., 2006; Lourenco et al., 2012; Odic et al., 2013), with similarities demonstrated between area and numerosity discrimination acuity, and interference of each variable on the processing of the other (Gebuis & Reynvoet, 2012a; Guillaume et al., 2013; Hurewitz et al., 2006; Leibovich & Henik, 2013; Lourenco et al., 2012; Tokita & Ishiguchi, 2013) leading to the suggestion that the ANS may not be numerosity-specific, but may represent numerous discrete and continuous quantities (Leibovich & Henik, 2013; Lourenco et al., 2012; but see Anobile, Cicchini, & Burr, 2013; Odic et al., 2013; Starr, Libertus, & Brannon, 2013). Indeed, EEG data presented by Gebuis and Reynvoet (2012a) suggest that cortical areas thought to be responsible for numerosity processing are strongly confounded by a response to additional visual cues such as dot diameter, convex hull, and array area. Such results support the suggestion that, at a neuronal and behavioural level, numerosity cues cannot be extracted independently from other, possibly confounding perceptual variables present within the stimuli (Gebuis & Reynvoet, 2012a; Szűcs et al., 2013). Further evidence is derived from studies implementing more stringent perceptual variable control (Gebuis & Reynvoet, 2011; Szűcs et al., 2013), where performance on the hardest trials (smallest numerosity ratio) may be significantly below chance when multiple visual confounds are manipulated (i.e. convex hull, dot diameter, density; the task becomes 'very incongruent'). A recent study directly investigating the impact of other perceptual variables on numerosity discrimination suggests that performance on ANS tasks is mostly driven by numerosity processing, but that a significant amount of the variance in task acuity can be explained by the influence of dot density and size (DeWind, Adams, Platt, & Brannon, 2015). On the contrary, when measuring both area and numerosity abilities with a non-symbolic discrimination paradigm, Guillaume et al. (2013) found that acuity on each task was unrelated, and that mathematical achievement correlated with numerosity discrimination but not area discrimination acuity. Such findings suggest a specific numerosity processing system separate from the processing of other quantities. Participants with poorer mathematical achievement were more susceptible to influence from the cumulative area of dot sets than those with higher mathematical ability

(Guillaume et al., 2013), reflecting other findings in the literature (e.g. Fuhs & McNeil, 2013; Gilmore et al., 2013) of a relationship between mathematical attainment and the ability to ignore incongruent perceptual variables during ANS tasks. Therefore, although research has attempted to disentangle the processing of numerosity and other perceptual variables, it remains unclear to what extent perceptual variables such as dot area and size may interfere with the processing of numerosity, and how different methods used to control for the influence of perceptual variables may affect measures of ANS acuity.

8.1.5 ANS acuity in ageing

Inhibitory control is known to decline in normal ageing (Cappelletti et al., 2014; Hasher & Zacks, 1988). Should performance on incongruent ANS trials be mediated by inhibition (Cappelletti et al., 2014, 2015), older participants may be expected to show even stronger 'Stroop-effects' during such tasks. Their performance during incongruent trials may therefore be poorer than younger adults, and the difference between their performances on congruent compared to incongruent trials may be larger (Cappelletti et al., 2014). Further, we may expect to see even stronger effects of anticorrelated compared to incongruent trials on older adults' performance compared to that of younger adults. Only two studies have so far directly investigated the ANS in ageing, with Cappelletti et al. (2014) using briefly displayed (200ms) congruent and incongruent dot arrays. In chapter 2, ANS acuity in ageing was investigated using the same size controls as Cappelletti et al. (2014). However, the effect of using anticorrelated trials during an ANS task has yet to be investigated in ageing. If reduced inhibitory control in older adults results in poorer performance during incongruent trials, declined performance may be predicted to be further exacerbated during anticorrelated trials, producing a stronger congruency effect than incongruent trials.

8.1.6 The current study

Because findings in the ageing literature regarding the acuity of the ANS are contradictory, and have not yet included anticorrelated trials in measures of ANS acuity as in younger populations, the current study aims to directly test whether using incongruent or anticorrelated trials may affect ANS acuity in ageing. Additionally, the current study will include measures of inhibitory control to investigate relationships between ANS task performance and inhibition in ageing. ANS acuity will be measured in terms of accuracy, RTs, and w_s in a group of younger and older adults using congruent, incongruent, and anticorrelated ANS trials. Further, the convex hull of each trial will be calculated, with trials identified as either convex hull congruent (the more numerous set has the larger convex hull), or convex hull incongruent (the more numerous set has the smaller convex hull). The study will therefore investigate: 1) whether performance during anticorrelated and incongruent trials is similar, or whether anticorrelated trials lead to further declined performance compared to incongruent trials, 2) whether, due to reduced inhibitory control, performance during anticorrelated trials as well as incongruent trials is poorer for the older group compared to the younger group, and 3) whether convex hull congruency affects ANS acuity measures, and how convex hull congruency interacts with size congruency and age.

8.2 Method

8.2.1 Participants

40 participants were recruited: 20 older adults aged 62 - 70 (14 females ; M = 65, SD = 2.9) and 20 younger adults aged 18 - 24 (16 females; M = 20, SD = 1.8). One older participant's data was excluded from the analyses due to a Weber fraction > 4 SDs from the mean (as in Halberda et al., 2012).

8.2.2 Materials and procedure

Control measures included the Mini Mental State Exam (MMSE), Geriatric Depression Scale (GDS), Spelling, Calculations, Colour Stroop, and Number Stroop (see p.28, chapter 2 for a detailed discussion of materials; Stroop procedures reported in chapter 3, p.58). Data were collected in the same testing session as data for chapter 3 in a fully counterbalanced manner. Panamath ran from Java, and the Number Stroop tasks from E Prime 2.

Approximate Number System: There were two within-subject factors, size control with 3 levels: congruent, incongruent, and anticorrelated, and ratio bin with 4 levels: 1.1-1.19, 1.19-1.28, 1.32-1.43, and 2.28-2.47. There were between 5 and 21 dots per coloured set. Participants initiated each trial by pressing the space bar. Separated dot displays appeared on a grey background simultaneously for 200ms (yellow on the left, blue on the right), followed by a 200ms backward mask. Participants responded as quickly as possible without sacrificing accuracy using the 'A' (yellow) and 'L' (blue) keys covered in correspondingly coloured dots. There were twelve possible trial types (3x size condition, 4x ratio bin), with a total of 420 trials.

8.3 Results

Firstly, in order to investigate the effect of age and area congruency on ANS acuity, mixed ANOVAs were conducted on Weber fractions, accuracy and RTs, with dot-size congruency (congruent, incongruent, and anticorrelated) as a within-subjects factor and age group (older or younger) as a between-subjects factor. Secondly, the effect of convex hull on ANS acuity in the younger and older groups was investigated, followed by correlations between ANS acuity and control measures. RT outliers were removed using an individual 3xSD cut off (1.8 % of data removed). There were no speed-accuracy trade-offs in either group (p_s > .1). Where sphericity was violated, Greenhouse Geisser corrections apply.

8.3.1 Weber fraction

Congruent, incongruent and anticorrelated Weber fractions for each participant were calculated. There were no main effects of congruency (p > .3) or age on w (p > .6), and no interactions. However, Figure 22 shows a tendency towards poorer performance as trials become 'more incongruent' for the younger group.

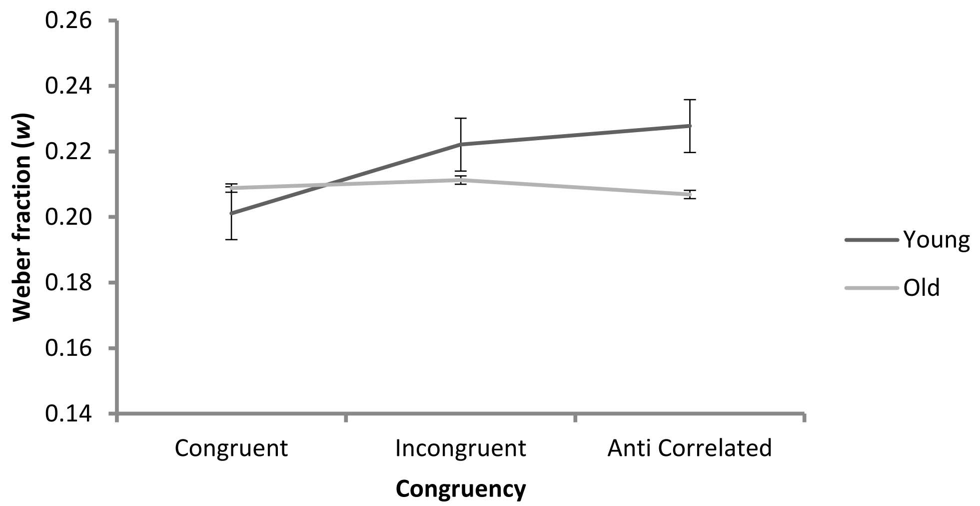

Figure 22: Weber fractions for old and young participants during each dot-size congruency condition

8.3.2 Accuracy

There were no main effects of congruency on accuracy ($p > .4$) or age group ($p > .7$), and no interactions, reflecting analyses on w_s. Figure 23 shows a similar behavioural pattern to that in Figure 22.

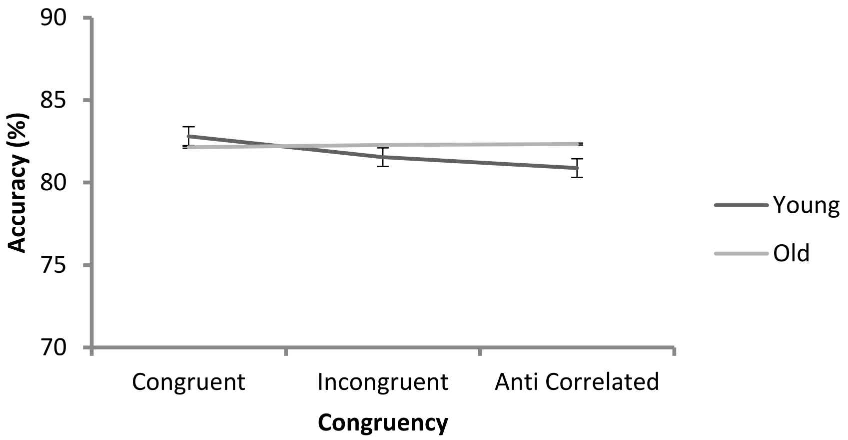

Figure 23: Accuracy for old and young participants during each dot-size congruency condition

8.3.3 RTs

There was a main effect of congruency on RTs ($F(2, 74) = 5.54$, $p < .01$), with pairwise comparisons indicating that responses to anticorrelated trials (M = 901.33ms, SD = 346) were slower than congruent trials (M = 882.30ms, SD = 323: $p < .01$), and that responses were also slower to incongruent (M = 899.67ms, SD = 351) compared congruent trials ($p < .05$). However, the difference between RTs on anticorrelated and incongruent trials did not reach significance ($p > .7$). Further, there was no main effect of age group ($p > .1$), and no interaction between age group and congruency ($p > .6$). The results in Figure 24 show a slightly slower performance overall for the older group, but a similar behavioural pattern of responses between groups.

These preliminary analyses on dot size control suggest that participants appear to be mostly unaffected by dot size congruency, apart from in speed of response, where incongruent and anticorrelated trials resulted in slower responses than congruent trials.

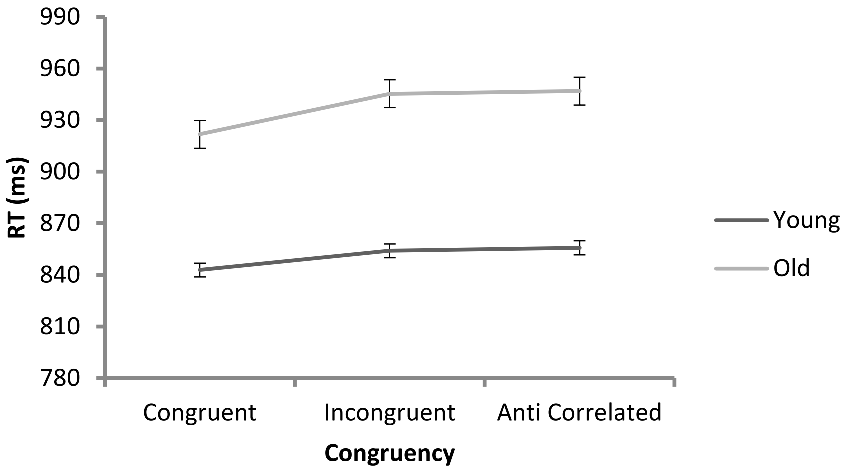

Figure 24: RTs for old and young participants during each dot-size congruency condition

8.3.4 Analyses of convex hull

The convex hull of the blue and yellow dot arrays and the congruency of convex hull with numerosity were calculated for each trial[iii] (Graham, 1972, as in Clayton et al., 2015). The convex hull represents the perimeter of each dot display (see Figure 25). Mixed ANOVAs on RTs and accuracy were conducted, with age group as a between-subjects factor, and dot-size congruency (congruent, incongruent, and anticorrelated) and convex hull congruency (congruent, incongruent) as within-subjects factors. Main effects of convex hull and interactions between dot-size congruency, convex hull congruency, and age group will be discussed. It was expected that convex hull is an important cue to numerosity during non-symbolic comparison tasks (Clayton & Gilmore, 2014; Gebuis & Reynvoet, 2011, 2012b). Therefore, it was anticipated that performance would be poorer during trials where convex hull is incongruent to numerosity (i.e. the most numerous set has the smaller convex hull).

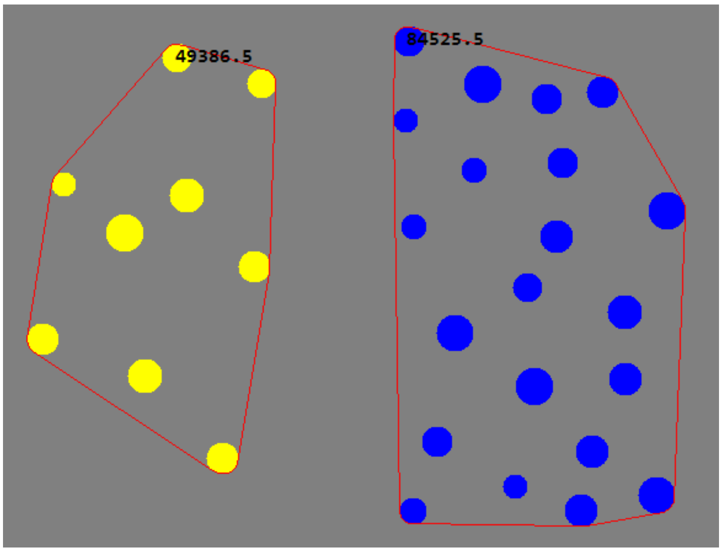

Figure 25: A separated dot display with the convex hull of each set depicted by a red line

8.3.5 Accuracy

There was a main effect of convex hull congruency ($F(1, 74) = 252.99$, $p < .001$), with a higher error rate during convex hull incongruent (M = 72.95%, SD = 4) than convex hull congruent trials (M = 84.29%, SD = 4: Clayton & Gilmore, 2014; Gebuis & Reynvoet, 2012c). There was no main effect of age group ($p > .6$). There was an interaction between convex hull congruency and dot-size congruency ($F(2, 74) = 8.20$, $p < .01$; see Figure 26). Contrasts indicate that, during convex hull congruent trials, accuracy is higher in dot-size congruent (M = 85%; SD = 4) than incongruent trials (M = 83%, SD = 5; $p < .01$), but the difference between accuracy on incongruent and anticorrelated trials (M = 84%; SD = 4) was marginally significant ($p = .058$), and the difference between congruent and anticorrelated trials did not reach significance ($p = .513$). This suggests that when convex hull is congruent to numerosity, performance reflects that found in prior analyses, whereby accuracy is higher during congruent trials compared to incongruent and anticorrelated trials. Conversely, during convex hull incongruent trials, accuracy was significantly higher for area incongruent (M = 77%; SD = 10) compared to area congruent trials (M = 71%; SD = 10: $p < .01$), and during incongruent compared to anticorrelated trials (M = 72%; SD = 9: $p < .05$). However, the difference between accuracy on congruent compared to anticorrelated trials was non-significant ($p = .514$). Therefore, when convex hull is incongruent to numerosity, it interacts with dot-size congruency in that conflicting congruencies (i.e. congruent dot-size but incongruent convex hull) lead to poorer performance. This suggests that participants rely on perceptual variables during a numerosity task, particularly convex hull, and that when cues from multiple perceptual variables are contradictory, performance declines. Finally, an interaction between convex hull congruency and age group ($F(1, 74) = 6.53$, $p < .05$) appears to be due to a stronger effect of convex hull congruency on accuracy for the older adults (i.e. a steeper decline in accuracy between convex hull congruent and convex hull incongruent stimuli: see Figure 27), although independent *t*-tests show no significant differences between older and younger adults' accuracies on convex hull congruent and incongruent trials ($p_s > .05$), reflecting the non-significant main effect of age.

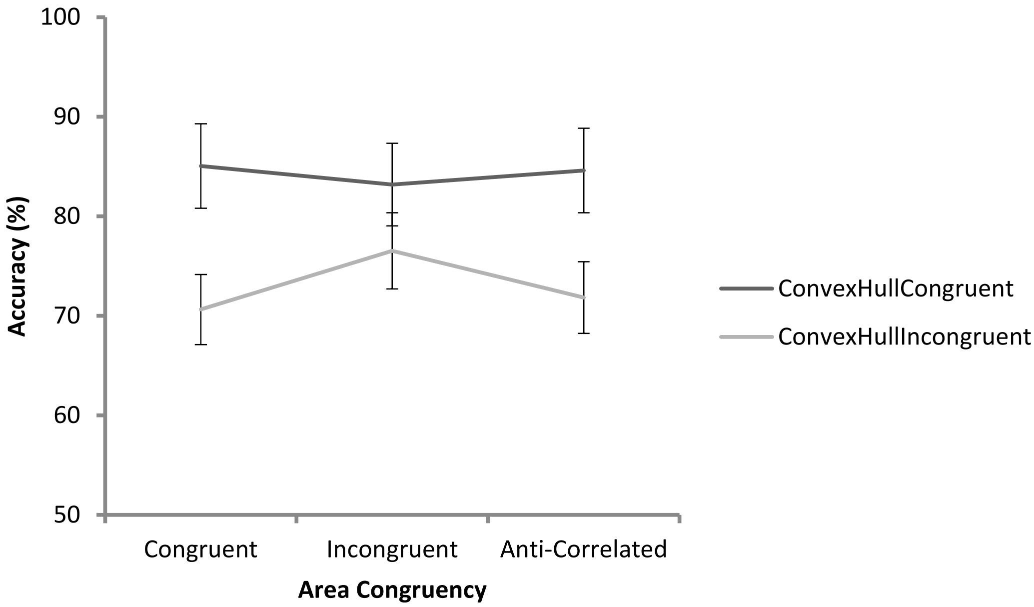

Figure 26: Interaction between convex hull congruency and dot-size congruency on accuracy

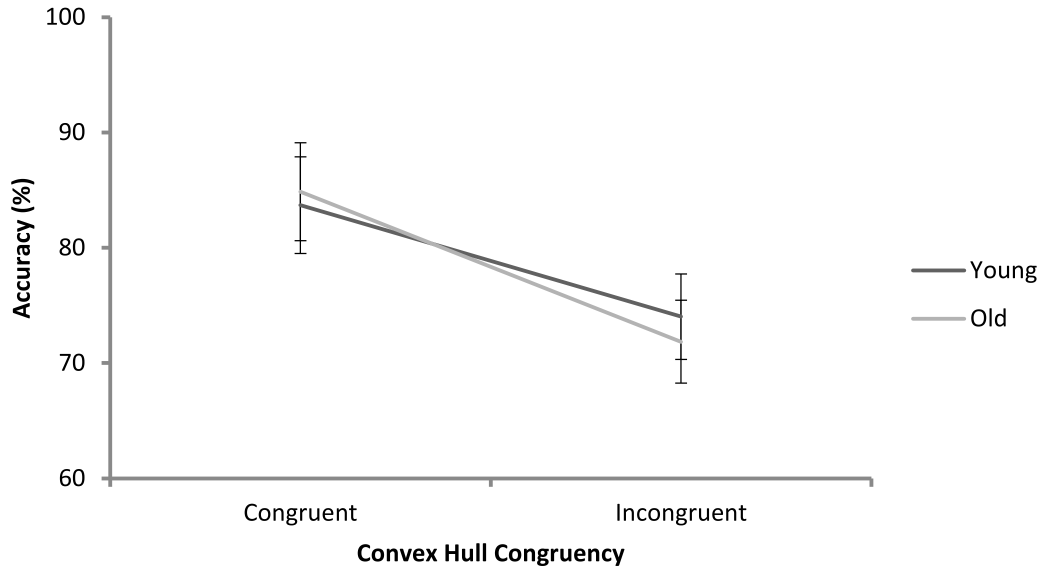

Figure 27: Interaction between convex hull congruency and age on accuracy

8.3.6 RTs

There was a main effect of convex hull congruency on RTs ($F(1, 74) = 38.71$, $p < .001$), with faster responses during convex hull congruent (M = 886.04ms, SD = 331) than convex hull incongruent trials (M = 932.13ms, SD = 378). The main effect of age was marginally non-significant ($F(1,37) = 3.459$, $p = .071$), with slightly slower RTs in the older group (M = 960ms, SD = 389) compared to the younger group (M = 858ms, SD = 280). Further, there was an interaction between convex hull congruency and age group ($F(1, 74) = 9.42$, $p < .01$), which appears to be due to a stronger effect of convex hull congruency on RTs for the older adults (see Figure 28). Separate analyses per age group revealed significant convex hull congruency for both groups. Therefore, independent *t*-tests were conducted between RTs on convex hull congruent and incongruent trials for younger and older adults, demonstrating significantly faster RTs for younger (M = 872ms, SD = 140) compared to older participants (M = 997ms, SD = 218) on convex hull incongruent trials ($t(37) = -2.15$, $p = .038$), but similar RTs on convex hull congruent trials ($p = .147$). These results suggest that when convex hull is incongruent to numerosity, older adults' speed of response is somewhat more affected than younger adults'. However, the groups show similar RTs during convex hull congruent trials.

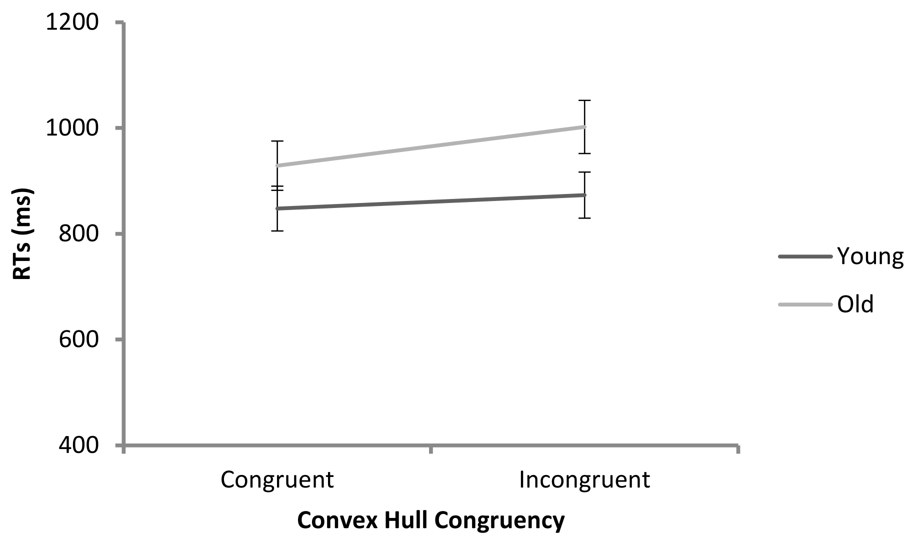

Figure 28: Interaction between convex hull congruency and age on RTs

8.3.7 Control measures

T-tests were conducted to investigate age group differences in terms of years of education, spelling, mathematical achievement and interference on the colour and number Stroop tasks. An interference effect (RT on incongruent trials – RT on neutral trials) was calculated for correct trials on the magnitude number Stroop task. Years of education were similar between groups ($p > .2$). Older adults scored higher on the spelling task (M = 83%, SD = 10) than younger adults (M = 74%, SD = 7; $t(37) = -2.975$, $p = .005$: e.g. Cappelletti et al., 2014; Hedden & Gabrieli, 2004; Watson et al., 2005). The same pattern applied to mathematical achievement, with older adults achieving higher scores (M = 88%, SD = 9) than younger adults (M = 70%, SD = 13; $t(33.29) = -5.43$, $p < .001$: Cappelletti et al., 2014). Older adults showed more interference during the colour Stroop task (M = 15s, SD = 5) than younger adults (M = 7s, SD = 3: $t(27.58) = -5.70$, $p < .001$), reflecting reduced inhibitory control in ageing (Hasher & Zacks, 1988; Kramer et al., 1994). However, there was no significant difference between groups for number Stroop interference ($p > .1$).

In order to investigate relationships between control measures and ANS acuity, correlations were conducted on mathematical achievement, spelling, interference, and ANS acuity separately for older and younger adults. ANS acuity did not correlate with any control measures for the younger group ($p_s > .05$). However, for the older group, higher mathematical achievement correlated with higher spelling scores ($r = .586$, $p = .008$), and higher spelling scores were also related to a smaller colour Stroop interference effect (r = -.458, p = .049). Correlations between mathematical achievement and anticorrelated accuracy (r = -.452, p = .052), anticorrelated w (r = .442, p = .058), and between higher mathematical achievement and lower colour Stroop interference (r = -.405, p = .085) all approached significance. These results appear to reflect a tendency in the older group toward a relationship between higher mathematical achievement and superior performance during anticorrelated trials on the non-symbolic comparison task, and between higher mathematical achievement and smaller colour Stroop interference (i.e. better inhibitory control).

8.4 Discussion

The current study aimed to investigate the impact of dot-size and convex hull congruency on ANS acuity in younger and older adults. ANS acuity appeared largely unaffected by dot size congruency. Anticorrelated trials do not therefore appear to create a stronger Stroop-like effect than incongruent trials. However, differences in response speed between both incongruent and anticorrelated trials compared to congruent trials suggests that resolving the incongruency of surface area to numerosity may require an extra cognitive step only visible in RT analyses, as this incongruency is resolved, and an accurate response provided. Further, convex hull congruency appeared to exert a stronger effect on numerosity comparison acuity than dot size congruency, with the effect of an incongruent convex hull exacerbated by ageing.

The current results suggest that using either incongruent or anticorrelated dots should not significantly affect ANS acuity in terms of accuracy and *w*, although response speed was affected. Conversely, analyses on convex hull congruency provide further insight into the perceptual demands present during non-symbolic numerosity processing. For all participants, an incongruent convex hull resulted in slower and less accurate responses (Clayton & Gilmore, 2014). However, older adults' performances were somewhat more negatively affected by an incongruent convex hull than younger adults'. This result may indicate that ageing, possibly due to slower processing speeds (Salthouse, 1996) and poorer inhibitory control (Hasher & Zacks, 1988), affects the efficiency of the first step of inhibiting a response based on incongruent convex hull prior to responding to numerosity (reflecting similar findings for size control: Cappelletti et al., 2014). Further, such results suggest that convex hull congruency exerts a more substantial effect on the processing of numerosity than dot size (Clayton & Gilmore, 2014), particularly in ageing. Analyses of accuracy during convex hull congruent and incongruent trials provided a curious finding: during convex hull congruent trials, an expected pattern of behaviour emerged, in that accuracy was higher during dot-size congruent than incongruent trials. However, during convex hull incongruent trials, performance on dot-size *incongruent* trials was more accurate than during dot-size *congruent* trials (an advantage for incongruent over congruent trials was also found in children by Keller and Libertus (2015), although the contribution of convex hull is unclear). Moreover, there was no difference between performance on congruent and anticorrelated trials, but higher accuracy during incongruent compared to anticorrelated trials. These findings are intriguing; performance on convex hull incongruent trials appears to be facilitated by dot area being *incongruent* to numerosity. A possible explanation for such a finding is that contradictory perceptual variable congruency (incongruent convex hull but congruent dot-size) may lead to poorer performances. Conversely, as the more numerous set has a smaller convex hull and the cumulative area of each set is equal, the more numerous set may appear more densely arranged on the screen due to its smaller convex hull (for an example see Figure 29). If this were the reason for higher accuracy on such trials, it would perhaps be expected that a similar pattern of behaviour would be found for performance on anticorrelated and convex hull incongruent trials. However, non-significant differences between performances on incongruent compared to anticorrelated trials in prior analyses may explain the absence of such a finding. Further, as the average dot size in the larger set is smaller during an anticorrelated trial, this may reduce the perceived density of the dots. Although density is suggested to be highly correlated with total cumulative area (Clayton, Gilmore, & Inglis, 2015; Gebuis & Reynvoet, 2012b), future research would benefit from investigating the impact of density on non-symbolic numerical abilities in ageing as discussed above. This appears to be particularly pertinent to the current study, as it is possible that perceived density may impact upon non-symbolic numerical skills in ageing. The current results may have been clearer with a larger sample size and more statistical power. However, such initial findings support the suggestion that convex hull congruency must be considered when analysing ANS acuity, as it may play a more significant role in numerosity processing than other confounding perceptual variables such as dot size (Clayton & Gilmore, 2014; Gebuis & Reynvoet, 2011). Moreover, such effects may be stronger for older adults due to their reduced inhibitory control (Cappelletti et al., 2014; Hasher & Zacks, 1988; Salthouse, 1996), diminished useful field of view (Lemaire & Lecacheur, 2007), or slower eye movements (Spooner et al., 1980; Warabi et al., 1984).

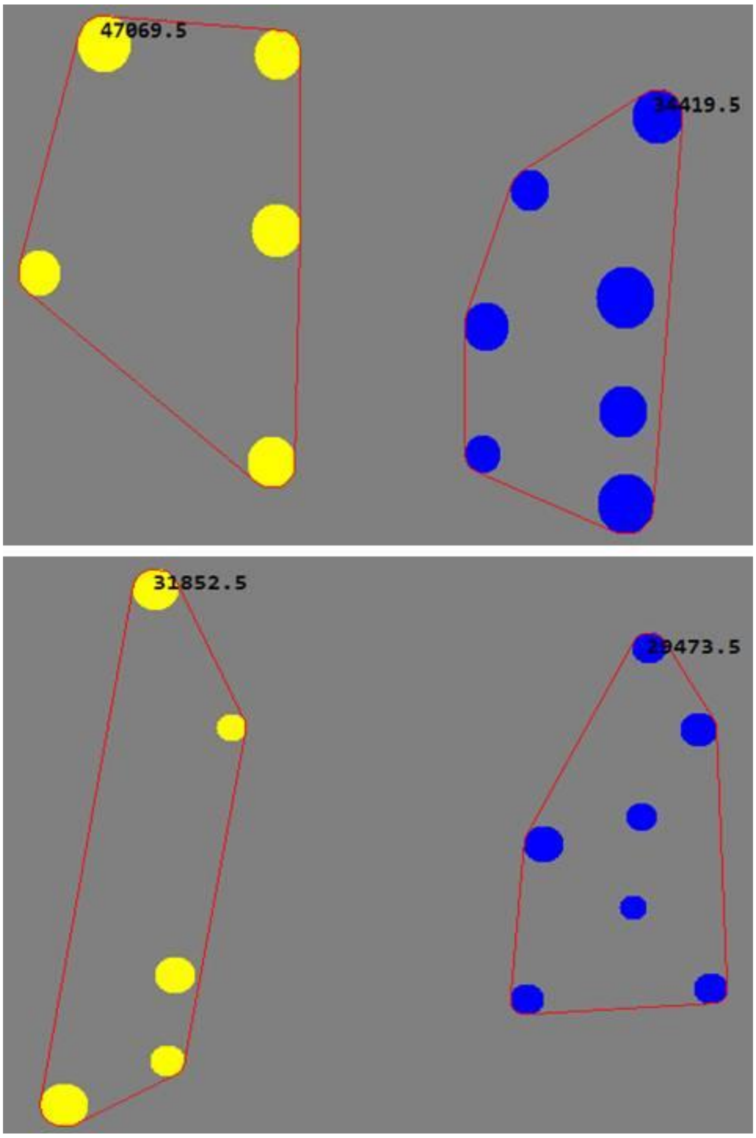

Figure 29: Two examples of convex hull incongruent trials, with congruent dot-size (top) and incongruent dot-size (bottom). When convex hull is incongruent, but dot size is congruent (top image), the more numerous dot set appears more densely arranged on-screen.

Although dot-size congruency does not appear to affect ANS acuity in this study, such methodological variations may mediate the relationship between the ANS and other cognitive abilities. Indeed, throughout the literature correlations have been found between mathematical achievement and performance on incongruent trials only (Gilmore et al., 2013), possibly due to inhibitory control mediating the link between ANS acuity and mathematical achievement (Clayton & Gilmore, 2014; Fuhs & McNeil, 2013; Gilmore et al., 2013; Szűcs et al., 2013). In the current study, ANS acuity was found to be marginally related to mathematics achievement for performance on anticorrelated trials (*w* and accuracy) in the older group only. Further, for the older adults a smaller colour Stroop interference effect was related to better mathematical achievement. Such findings, although not reaching statistical significance, appear to demonstrate an emerging relationship between mathematical achievement and an older participant's ability to inhibit an incorrect response based on anticorrelated dot size. Such a finding provides some support to the suggestion that correlations found between ANS acuity and mathematical achievement may be mediated by inhibitory control (Clayton & Gilmore, 2014; Fuhs & McNeil, 2013; Gilmore et al., 2013). A significant relationship may only have emerged for the older group in the current study due to older adults' deteriorated inhibitory control (Hasher & Zacks, 1988): the colour Stroop task may not have been sufficiently sensitive to accurately measure variation in inhibition in the younger group, who have overall stronger inhibitory control. It is therefore important to consider and directly analyse the effects of perceptual variable control on ANS acuity and the contribution of inhibitory control in order to reliably test the relationship between ANS acuity and other cognitive abilities, particularly mathematical achievement.

Further research on congruency effects during ANS tasks in all populations, including older adults, may benefit from directly measuring area discrimination acuity (e.g. Guillaume et al., 2013; Lourenco et al., 2012) to further investigate how the processing of other quantities may be affected by ageing. Such investigation would allow for comparison between numerosity and area/dot-size discrimination acuity, providing further insight into the relationship between such abilities in ageing. The current study could be further improved by adopting a larger sample size for increased statistical power, as some marginal effects were found. Additionally, a large number of trials (420) were used to reliably calculate acuity for each congruency condition. Trial number may influence ANS acuity, and may affect participants' sensitivity to confounding perceptual variables (Clayton & Gilmore, 2014). The inevitable repetition of each condition may have resulted in a practice effect (e.g. Tokita & Ishiguchi, 2010), desensitising participants to the more difficult dot-size incongruent and anticorrelated trials, therefore potentially masking size congruency effects which may have emerged with fewer trials. However, despite using multiple trials, convex hull congruency exerted a stronger effect on ANS acuity than size congruency, particularly in older adults. By directly measuring convex hull, scarcely applied in research utilising the Panamath software, the current findings emphasise the requirement for researchers using similar paradigms to consider the influence of other perceptual variables not directly accounted for by the software, particularly convex hull. Further, there is scope within research investigating ANS acuity in ageing to utilise alternative paradigms now available, which include more stringent controls of a multitude of perceptual variables (e.g. Gebuis & Reynvoet, 2011), or which directly measure the interference of other perceptual variables on numerosity discrimination precision (DeWind et al., 2015). Controlling only one perceptual variable (i.e. dot size) may be insufficent, as multiple visual cues are simultaneously extracted from non-symbolic stimuli alongside numerosity (Gebuis & Reynvoet, 2012a, 2012b). Indeed, perceptual variables such as convex hull and density (Gebuis & Reynvoet, 2011, 2012a), and numerosity range (Clayton & Gilmore, 2014) may influence numerosity judgements over and above dot size. The use of newer paradigms directly controlling such perceptual variables may therefore provide a more reliable and valid measure of the effect of ageing on ANS acuity, and on sensitivity to confounding perceptual variables during numerosity discrimination. The current study also highlights the importance of ANS task instructions given to participants, currently contradictory throughout the literature. Some researchers emphasise a speeded response (Gilmore et al., 2013; Inglis et al., 2011), whereas others appear to emphasise accuracy, as instructions given to participants on response speed are not included (e.g. Halberda et al., 2012; Libertus et al., 2011). Such discrepancies may mediate the effect of congruency on ANS acuity, as participants in different studies may use varying strategies, emphasising speed over accuracy or vice versa, further exacerbating problems inherent in comparing studies measuring the ANS.

Although the current study has limitations, it provides the first direct investigation of the three commonly used controls of dot-size congruency, with additional analysis of convex hull congrency during an ANS task in younger and older adults. The results show that ageing appears to affect sensitivity to incongruent dot size in terms of response speed, but not acccuracy and *w*. However, when convex hull is incongruent to numerosity, older adults show a particular deficit in ignoring this incongruency compared to younger adults, although this weakness during convex hull incongruent trials is only reflected by an interaction, with similar overall ANS acuity between groups. The current study supports the findings from chapter 2, whereby older and younger adults demonstarted similar ANS acuity regardless of dot area congruency. However, in chapters 2 and 5, congruency was found to affect numerosity discrimination for all participants, particularly when the dots were displayed in a spatially intermixed form (as in Cappelletti et al., 2014). Together, the results suggest that the presence of congruency effects on ANS acuity may be mediated by other stimulus display variables, such as whether dots are spatially intermixed or separated on-screen (see chapter 5). However, the current chapter emphasises the importance of measuring the contribution of other perceptual variables to numerosity judgements, particularly in older adults due to their reduced speed of processing and inhibition capacity (Cappelletti et al., 2014; Hasher & Zacks, 1988; Kramer et al., 1994; Salthouse, 1996). ANS acuity measures may therefore indicate age-related decline due to the effect of incongruent perceptual variables, rather than deteriorated non-symbolic numerical abilities specifically (Cappelletti et al., 2014).

9 General discussion

It is well established that several cognitive functions, including processing speed, inhibitory control, memory, executive functions, and problem solving gradually decline during the course of healthy ageing. However, the impact of cognitive ageing on numerical abilities is currently unclear, and was therefore directly addressed in the thesis. Although limited previous research investigated the impact of ageing on precise and procedural numerical skills such as arithmetic, conclusions were contradictory. Crucially, research regarding the effect of ageing on foundational numerical abilities was limited. This issue warranted further consideration due to the innate, primitive, and evolutionary nature of foundational numerical skills (Dehaene, 2009). Indeed, these abilities may potentially be spared in ageing due to their embedded nature. Basic numerical skills may potentially therefore be categorised as a preserved cognitive ability in older age, alongside functions such as emotional processing, autobiographical memory, vocabulary and verbal skills. Although a limited number of studies attempted to address the impact of ageing on foundational non-symbolic abilities, the effect of ageing on foundational *symbolic* abilities was yet to be directly tested. The series of studies presented within the thesis therefore aimed to directly study the impact of healthy ageing on foundational non-symbolic and symbolic numerical processing to determine whether such skills may constitute one of a few cognitive processes relatively unaltered by the course of ageing. Furthermore, the thesis addressed methodological factors present in the current literature which may mediate ageing effects on ANS acuity, as well as the contribution of other cognitive functions such as inhibitory control, verbal knowledge, and mathematical achievement.

9.1 Summary of findings

In order to ground the conclusions directly within the context of the findings, a brief summary of the findings from each study will be presented. In all experiments a series of control measures were taken, including mathematical achievement, inhibitory control, verbal abilities, and levels of education in order to carefully and systematically evaluate the impact of other cognitive functions and educational factors on the trajectory of foundational numerical abilities in ageing.

9.1.1 Section 1: Foundational numerical abilities in ageing

The thesis was split into two major sections, with section 1 addressing the impact of ageing on foundational non-symbolic and symbolic numerical abilities. In chapter 2, the first direct comparison of non-symbolic and symbolic foundational numerical skills in younger and older adults was presented. It was concluded that, due to similar accuracy and w_s between age groups, non-symbolic numerical abilities are preserved in healthy ageing. Furthermore, foundational symbolic abilities were enhanced in the older group, with analyses indicating an explicit contribution of older age to superior symbolic skills. Chapter 3 utilised a numerical priming paradigm in order to directly investigate the finding of enhanced symbolic numerical abilities with older age in chapter 2. Reflecting the findings from chapter 2, older adults presented higher accuracy on the numerical priming task than younger adults. Moreover, older adults demonstrated a more embedded symbolic numerical representation in the form of stronger congruency priming effects and size effects during number priming. Chapters 2 and 3 therefore presented a picture of enhanced symbolic numerical processing with ageing due to the role of lifetime exposure to and experience with using numbers. This suggestion is particularly pertinent to small numbers (e.g. 1-9) due to their frequency in daily life (Reynvoet et al., 2009). The potential impact of life experience using numbers on foundational numerical skills in older age was tested in chapter 4 by comparing foundational numerical abilities in older adults with a degree in mathematics and older adults without further mathematical education. Results indicated that stronger numerical experience in the mathematically educated older group did not influence the acuity of non-symbolic and symbolic numerical skills in ageing. Indeed, both groups presented similar foundational numerical acuity, supporting the suggestion that non-symbolic numerical skills are preserved in ageing due to their innate, embedded nature, whereas symbolic numerical abilities are enhanced with older age due to the contribution of lifespan experience using numbers. Older adults however demonstrated an overall pattern of general slowing compared to younger adults (Salthouse, 1996).

9.1.2 Section 2: Investigating the reliable measurement of ANS acuity in ageing

The second section of the thesis presented two experiments which examined and compared the impact of measuring ANS acuity in ageing with varying methods, whilst also identifying the influence of inhibition and mathematical achievement on non-symbolic numerical skills in ageing. Chapter 5 compared ANS acuity of younger and older adults when using either spatially separated or spatially intermixed dot displays. The study demonstrated the importance of task design in measuring non-symbolic numerical abilities in ageing, as the method in which stimuli are presented may affect acuity. Indeed, older adults presented a particular weakness when dots were spatially intermixed, compared to when they were spatially separated. The negative impact of using spatially intermixed dot displays on the measurement of ANS acuity in ageing appears to be driven by the increased inhibitory load of the intermixed design. Therefore, chapter 6 aimed to directly investigate the impact of perceptual variable congruency and the resulting inhibitory load on non-symbolic numerosity judgements in ageing. The effect of the average dot size and convex hull of dot displays on ANS acuity was tested, due to the potential for such manipulations to alter the complexity and therefore difficulty of numerosity discrimination tasks (Clayton & Gilmore, Gebuis & Reynvoet, 2012b). The results indicated that convex hull congruency may have a stronger effect on numerosity judgements compared to the impact of dot size, particularly in ageing. Participants, particularly older adults, appeared to be more driven to make a 'more' judgement based on a larger convex hull (i.e. larger perimeter of dot display), than due to a larger average dot size. The findings emphasise the importance of controlling and measuring the impact of multiple perceptual variables in order to determine the true impact of ageing on the foundational ANS.

In summary, the research presented within the thesis provides an original and significant contribution to the literature regarding numerical cognition in ageing, indicating that foundational numerical abilities are preserved in healthy ageing. Specifically, non-symbolic numerical abilities are preserved, and symbolic abilities enhanced in older age, likely due to lifetime exposure to and experience with symbolic number. Furthermore, the thesis demonstrates the importance of task design in reliably measuring non-symbolic numerical abilities in ageing, explicitly identifying methodological aspects which may lead to poorer ANS acuity in older adults. Furthermore, the findings also present implications for pathological ageing, in that the preservation of foundational numerical skills in healthy ageing may be compared with abilities on similar tasks in pathological ageing. Compared to stability in healthy ageing, deteriorated performance may indicate pathological processes.

9.2 Contribution and implications

The thesis provides implications not only for research regarding the effect of ageing on foundational numerical skills, but for the field of cognitive ageing more broadly, and for the reliable measurement of ANS acuity in all populations. This section will therefore address the implications for each factor, including primarily the impact of ageing on foundational numerical abilities and the reliable measurement of the ANS, followed by a brief discussion of the implications for hypotheses of inhibitory-deficit (Hasher & Zacks, 1988) and processing-speed decline (Salthouse, 1996) in ageing.

9.2.1 Foundational numerical abilities in ageing

Non-symbolic numerical abilities were found to be preserved in ageing. This pattern of similar non-symbolic discrimination between younger and older adults may be due to the preservation of an embedded, innate, evolutionary cognitive system (Dehaene, 2009). However, ageing was found to be associated with somewhat worse performance during incongruent trials on a non-symbolic task, with the impact of the congruency effect also mediated by task design (see below, 9.2.2). Further, older adults' poorer performance on incongruent trials did not result in overall poorer ANS acuity for older compared to younger adults.

A significant debate within the numerical cognition literature currently surrounds the role of foundational non-symbolic numerical abilities in mathematical achievement (see Chen & Li, 2014 for a review). The current findings suggest that ANS acuity is not related to mathematical achievement in adulthood and older age. A correlation between ANS acuity measures and mathematics scores only approached significance when the inhibitory load of the task increased, e.g. when using intermixed dot displays (Cappelletti et al., 2014), during incongruent trials (Fuhs & McNeil, 2013; Gilmore et al., 2013), or a mix of the two. This may be due therefore to a relationship between mathematical achievement and an inhibitory component of the ANS task (Bull & Scerif, 2001; Clayton & Gilmore, 2014; Fuhs & McNeil, 2013; Gilmore et al., 2013; St Clair-Thompson & Gathercole, 2006). The findings therefore have significant implications for the debate within the numerical cognition literature regarding the relationship between ANS acuity and mathematical achievement, particularly in adulthood and older age. The results support the notion that ANS acuity may reach a maximum in adulthood (Castronovo & Göbel, 2012; supported by similar ANS acuity in younger and older groups), reducing the strength of a correlation between the ANS and mathematical ability in adults. The findings therefore support those of previous research in adults where no correlation between ANS acuity and mathematics scores was found (Castronovo & Göbel, 2012; Inglis et al., 2011; Price et al., 2012). Moreover, the thesis supports the suggestion that inhibitory control may mediate the ANS-mathematical ability link (Clayton & Gilmore, 2014; Fuhs & McNeil, 2013; Gilmore et al., 2013; Szűcs et al., 2013).

Symbolic foundational numerical abilities were found to be enhanced in ageing. Stronger symbolic skills appear due to a more embedded symbolic numerical representation in ageing. This stronger symbolic representation in older adults is likely attributable to lifetime exposure to numbers (Reynvoet et al., 2009), and a life span's experience using and manipulating numbers. It has been suggested that stronger foundational symbolic abilities, alongside consistently higher mathematical achievement scores in older adults, may represent a cohort effect caused by qualitative differences between younger and older adults' mathematical education (Geary & Lin, 1998). However, detailed analyses revealed a more significant contribution of being older to stronger symbolic skills than that of higher mathematical achievement or years in education. Therefore, the findings support the suggestion that lifetime exposure to numbers enhances symbolic numerical representations, leading to strengthened skills across the lifespan, with the strongest abilities in older age (as with a stronger SNARC effect in older age: Wood et al., 2008).

Finally, older adults consistently demonstrated enhanced mathematical and spelling skills compared to younger adults. These results reflect similar findings of enhanced verbal skills (Cappelletti et al., 2014; Geary & Lin, 1998; Hedden & Gabrieli, 2004; Watson et al., 2005) and stronger mathematical ability (e.g. Salthouse & Kersten, 1993) in older age, further demonstrating the robustness of crystallised intelligence in ageing (Christensen, 2001; Deary et al., 2009; Hedden & Gabrieli, 2004).

9.2.2 The reliable measurement of ANS acuity in ageing

Overall, the findings suggest that different ANS task designs may mediate the level of inhibitory load, affecting ANS acuity in all age groups. Firstly, the findings regarding the effect of dot size congruency on ANS task performance in ageing were mixed. In all studies, younger and older participants demonstrated a congruency effect, with poorer performances during incongruent compared to congruent trials. However, this was not the case in the final study (chapter 6). Mostly, the congruency effect only interacted with age when other variables in the task were also manipulated (e.g. using an intermixed dot display), or for RT scores only. Therefore, dot size congruency appears to have a lesser impact in terms of age differences in ANS acuity, particularly during separated dot displays, compared to convex hull. Convex hull congruency was found to significantly affect ANS task performance in ageing. Further, dot size and convex hull congruency interacted, in that contradictory congruencies (e.g. incongruent convex hull but congruent dot size) led to poorer ANS acuity. However, as with all prior studies these effects did not lead to a group effect in terms of overall ANS acuity (accuracy and w_s). The results therefore demonstrate that manipulations of perceptual variables may impact the measurement of ANS acuity, particularly in ageing, although similar overall ANS acuity was consistently found between groups, supporting the preservation of ANS acuity in healthy ageing (Cappelletti et al., 2014, 2015).

The most important task design factor in terms of its potential to impact the measurement of overall ANS acuity and group comparisons was whether a spatially separated or intermixed dot display was used. Intermixed dot displays were somewhat more difficult for older compared to younger adults, with ANS acuity derived from intermixed displays related to inhibitory control and/or increasing age in the older group. Furthermore, incongruent trials in particular were more difficult for older adults when the dots were intermixed than when they were separate. These findings support the suggestion that task design may mediate the inhibitory load of a paradigm designed to assess ANS acuity (Clayton & Gilmore, 2014; Szűcs et al., 2013). Moreover, the findings suggest that intermixed displays may be particularly difficult for older adults, likely due to their declined inhibitory control (Hasher & Zacks, 1988; Kramer et al., 1994), providing an explanation for reduced ANS acuity in ageing when intermixed dot displays are used (Cappelletti et al., 2014; Halberda et al., 2012) compared to when spatially separated designs are used (chapter 2: Norris et al., 2015). Older adults' difficulties during intermixed displays may be attributable to the many processing requirements of the task, all of which must be performed within the stimulus onset time (200ms) or soon after: firstly, participants must resolve the overlapping dot displays (Szűcs et al., 2013), followed by the need to inhibit a response based on dot size during incongruent trials, finally resulting in making a numerosity judgement (see Figure 30). It appears therefore that separated dot displays may yield more reliable and valid ANS acuity measures and group differences, particularly when comparing groups with poorer inhibitory control, such as older adults. Finally, additional cognitive and biological processes may reduce older adults' intermixed ANS task performance, including slower processing speed (Salthouse, 1996), poorer useful field of view (Lemaire & Lecacheur, 2007), and slower eye movements (Spooner et al., 1980; Warabi et al., 1984). Such factors require further attention in future research.

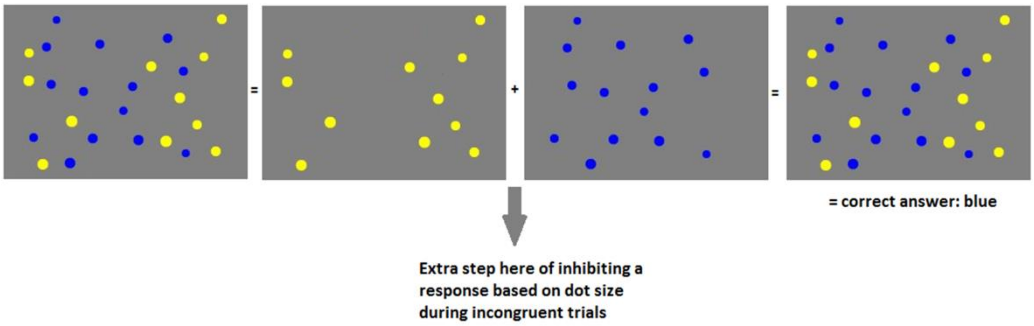

Figure 30: A demonstration of the cognitive steps required during an intermixed ANS task, which may be negatively affected by age-related declines in cognitive and biological processes: Firstly, participants are presented with an intermixed dot display. Participants must resolve the overlapping displays (Szűcs et al., 2013), potentially by processing each set one at a time whilst inhibiting the presence of the other set. Finally, participants may make a numerosity judgement. This process may also be further complicated by the necessity to inhibit a response based on dot size during an incongruent trial, and all steps must be completed in around the stimulus onset time of 200ms.

9.2.3 Inhibition-deficit hypothesis of ageing

The current findings support the suggestion that ageing is associated with a decline in inhibitory control, in line with the inhibitory-deficit theory of ageing (Cappelletti et al., 2014, 2015; Hasher & Zacks, 1988; Kramer et al., 1994). Older adults showed consistently higher interference effects on the colour Stroop task, and frequently displayed higher interference effects on the number Stroop task, although this effect was less reliable. In some of the studies presented within the thesis, the number Stroop did not detect a group difference in inhibitory control. A potential explanation for this finding is that older adults' superior symbolic numerical skills may have assisted during the number Stroop task. Indeed, older adults' more embedded symbolic numerical representation may have masked an inhibitory deficit in the number Stroop task. Further, in the physical component of the task, typical behavioural effects were not found (the distance effect). Future research would therefore benefit from using alternative interference measures, such as the go/no-go task (see section 9.4 for further discussion of this issue).

A deteriorated ability to inhibit irrelevant but salient information in ageing is further supported by performances on ANS tasks. Indeed, the second section of the thesis was devoted to investigating the reliable measurement of the ANS. When task difficulty was increased, such as when intermixed displays were applied, older adults demonstrated a weakness during incongruent trials, where inhibition of a response based on dot size is required. Further, older adults appeared less able to inhibit a response based on convex hull. These findings implicate declined inhibitory control during ANS task performance in ageing (as in Cappelletti et al., 2014, 2015). However, contrary to Cappelletti et al. (2014), impaired inhibitory control in the older group did not result in an overall group difference for ANS acuity. Moreover, older adults' stronger congruency priming effects during the number priming study may be suggested to be caused by poorer inhibitory control (Dehaene et al., 1998). However, this notion is not supported by the current results, as interference effects from the number Stroop task did not correlate with number priming performance. This suggests that stronger priming congruency effects in ageing may be due to a more embedded and automatically accessed symbolic numerical representation with age. Finally, data from chapter 4 suggest that older adults with a higher level of mathematical education may present stronger inhibition skills, as the group with a degree in mathematics demonstrated smaller congruency effects during the ANS task compared to older adult controls. The findings further support the necessity for inhibitory control during ANS tasks (Clayton & Gilmore, 2014; Szűcs et al., 2013) particularly in ageing, where inhibition is deteriorated (Cappelletti et al., 2014, 2015; Hasher & Zacks, 1988; Kramer et al., 1994). Moreover, the results further demonstrate preserved ANS acuity in ageing, unaffected by higher mathematical education.

9.2.4 Processing-speed decline in ageing

Finally, the thesis poses implications for the processing-speed decline theory of cognitive ageing. Broadly, the findings support an age-related decline in speed of processing. Firstly, older adults tended to perform more slowly in general than younger adults on all tasks (non-symbolic and symbolic comparison). However, a stronger non-symbolic ratio effect on RTs for the older group in chapter 2 may be attributed to transcoding: due to their more extensive experience with symbolic number, groups with higher mathematical attainment (older adults in this case) may transcode non-symbolic numerosities into their corresponding symbolic number before processing in relation to task demands (Castronovo & Göbel, 2012). This example of different patterns of response times between younger and older participants demonstrates the importance of further exploration of apparent age-related slowing during cognitive tasks, as other factors related to ageing may additionally contribute to apparent general slowing (i.e. life experience with symbolic numbers). Finally, our results support the suggestion that slower speed of processing in older age may interact with other age-related cognitive changes, such as poorer inhibitory control (Borella et al., 2008; Salthouse & Meinz, 1995; Verhaeghen & De Meersman, 1998). Analysis of congruent and incongruent trials during ANS tasks allowed for dissociation between general age-related slowing in overall responses from a specific slowing during incongruent trials when inhibition was required. In summary, the current findings support the notion of generalised slowing in ageing (Salthouse, 1996), but also the suggestion that some slowing, particularly whereby inhibition is required (i.e. during incongruent dot-size ANS trials and/or when dot displays are presented spatially intermixed), may be attributed to impaired inhibitory capacity in older adults (e.g. Cappelletti et al., 2014).

9.3 Recent publications relevant to the thesis

A recent article published by Cappelletti et al. (2015) is particularly pertinent to the current thesis, and warrants further discussion. In this study, a group of younger and older adults were administered an hour's training on a non-symbolic quantity discrimination task for five consecutive days. Participants were trained to discriminate sets of intermixed dots presented for 200ms (as in Cappelletti et al., 2014; Halberda et al., 2012), with 560 trials per training session. As in Cappelletti et al. (2014), stimuli were either dot-size congruent or incongruent. Cognitive training was paired with either parietal tRNS stimulation, or control stimulation groups of either sham or motor cortex stimulation. The study aimed to investigate whether ANS training, particularly when paired with parietal stimulation, would result in stronger ANS acuity in younger and older participants. The authors proposed that any increase in ANS acuity precision after training may be driven by improvements in learning either cue integration or inhibition. Cue integration refers to the process of integrating multiple visual cues during an ANS task (e.g. dot size). On the other hand, inhibitory control is relevant to potentially improved ANS acuity due to the necessity to inhibit a response based on dot size during incongruent trials. Firstly, ANS acuity was found to be similar between groups, reflecting the findings of the thesis. Secondly, post-training measures indicated improved ANS acuity in all participants after training, particularly when paired with parietal stimulation. Furthermore, older adults' stronger ANS acuity appeared to be driven by an improved ability to inhibit irrelevant variables during incongruent trials, performance on which was related to smaller interference effects on traditional inhibition tasks (e.g. number Stroop and the Navon task). Finally, successful learning to suppress other visual cues during an ANS task led to *reduced* performance for the older group on tasks measuring the discrimination of other perceptual variables such as space. This pattern of behaviour in the older group further supports the notion that inhibitory control is required during an ANS task, impacting in particular older adults' performance due to age-related inhibition decline (Cappelletti et al., 2014; Hasher & Zacks, 1988; Kramer et al., 1994). The findings therefore support conclusions made within the thesis, that the foundational, innate ANS is preserved in healthy ageing, but performance may be significantly affected by age-related decline in other cognitive functions, particularly inhibitory control (Cappelletti et al., 2014, 2015). This study therefore presents further implications for the field of numerical cognition in ageing and for the trainability of the ANS, whilst supporting the findings presented within the thesis.

Finally, in their recently published book chapter 'numerical cognition during cognitive ageing', Uittenhove and Lemaire (2015) provide a detailed account of age differences in arithmetical problem solving strategy use, but stress the requirement for future research to further investigate the impact of ageing on foundational numerical abilities such as the ANS and ENS. Further, the authors indicate the importance of simultaneously studying the impact of other cognitive factors on numerical task performance, most notably inhibition and speed of processing. The thesis has therefore directly addressed this requirement for a thorough investigation of foundational non-symbolic and symbolic numerical skills in ageing, whilst also studying the relationship between such basic numerical abilities and an array of other cognitive factors in ageing (mathematical and verbal skills, education level, and inhibitory control). The results indicate that overall, the ANS is preserved and the ENS enhanced in healthy ageing, with such findings mostly unrelated to mathematical achievement and verbal skills. However, performance on ANS tasks was affected by inhibitory control, with the second section of the thesis devoted to the further investigation of how methodological differences throughout the literature may mediate the inhibitory load of ANS tasks, affecting the reliable and valid measurement of the effect of ageing on ANS acuity.

9.4 Limitations and future research

9.4.1 Non-symbolic discrimination paradigm

As discussed within each chapter, the thesis has limitations which may be addressed by future research. Firstly, since beginning our data collection, the Panamath software (http://www.panamath.org/researchers.php : Halberda et al., 2008) has received some criticism within the literature, with some suggesting alternative paradigms which make better use of perceptual variable controls. Whereby such concerns have arisen, the thesis has attempted to address them in a few ways. Firstly, as in many other studies (Cappelletti et al., 2014, 2015; Clayton & Gilmore, 2012; Fuhs & McNeil, 2013; Gilmore et al., 2013), we have explicitly analysed younger and older adults' ANS task performance in terms of congruent and incongruent trials. Therefore, the implication that the paradigm presents a 'Stroop-like' effect, whereby participants must engage inhibitory processes, is directly addressed throughout the thesis. Secondly, as far as possible the limitation of the paradigm in not controlling multiple visual cues was addressed in the final experimental chapter (6) by calculating and assessing the impact of convex hull congruency on performances in ageing. Furthermore, the effect of using separated vs. intermixed dot displays was directly tested in chapter 5. However, it would be beneficial for future research to administer newer paradigms (e.g. Gebuis & Reynvoet, 2011), whereby multiple perceptual variable controls are applied (convex hull, dot density, dot size, total cumulative area, etc: see Figure 31). Further, direct investigation of the contribution of each visual cue to participant performance would provide additional insight into the impact such variables have on ANS acuity measurement in ageing (as in DeWind et al., 2015). Finally, in order to eliminate the impact of other perceptual variables on numerosity discrimination performance, younger and older adults could be submitted to an aurally-presented numerosity comparison task (e.g. Barth et al., 2003; Lipton & Spelke, 2004; and in infants: Izard et al., 2009).

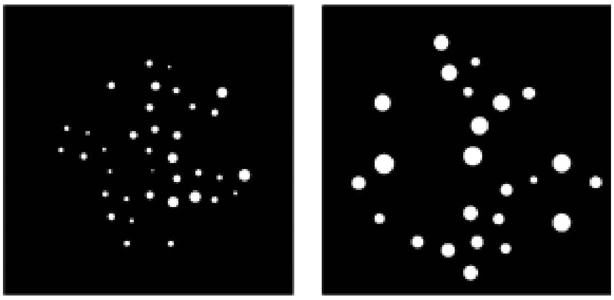

Figure 31: An example non-symbolic numerosity discrimination trial from Gebuis and Reynvoet (2011)

9.4.2 Visual acuity

Secondly, investigation of additional cognitive and biological factors which may potentially contribute to ANS task performance in ageing deserves further attention. Although inhibition was found to significantly impact older adults' performance during ANS tasks, particularly for the more visually complex intermixed dot displays, it remains unclear to what extent other aspects may contribute to older adults' poorer performance. Many other potential contributing factors have been suggested, including impaired visual acuity (Uittenhove & Lemaire, 2015), a reduction in useful field of view (Lemaire & Lecacheur, 2007), slower eye movements (Spooner et al., 1980; Warabi et al., 984), and reduced speed of processing in ageing (Salthouse, 1996). For example, poorer performance found during incongruent trials (see Chapter 5), particularly when intermixed dot displays are used (e.g. Cappelletti et al., 2014) may be partially mediated by the impact of ageing upon such visual processes. During an incongruent, intermixed trial, participants must first disentangle the intermixed arrays (Szűcs et al., 2013), followed by inhibiting an incorrect response based on incongruent visual cues, prior to making a decision regarding array numerosity (see 7.5, and Fig. 30, 9.2.2 for further discussion and a visual representation of each step). The process of disentangling the visual arrays may be more difficult for older adults due to slower eye movements or poorer visual acuity. This may therefore allow less time for older adults to deal with visual-cue incongruency during incongruent trials. To measure the impact that the ageing visual system may have on non-symbolic numerosity discrimination, the use of eye tracking technology would assess visual processes during an ANS task, whilst also addressing the possibility that older adults may adopt compensatory strategies due to poorer vision (Uittenhove & Lemaire, 2015). Moreover, the use of eye-tracking methods has yet to be applied to ANS research. Finally, future research may benefit from explicitly measuring visual acuity, in order to study a potential correlation between visual acuity and

ANS acuity in ageing (as with visual attention and mathematical achievement: Anobile, Stievano, & Burr, 2013).

9.4.3 Inhibitory control

Although the thesis aimed to assess the impact of declined inhibition on foundational numerical cognition using colour and number Stroop tasks, future research would benefit from using a battery of inhibition measures (e.g. Fuhs & McNeil, 2013). Although the colour Stroop showed consistent decline in older compared to younger participants (i.e. higher interference effects), the number Stroop task was not as successful in revealing group differences, potentially due to older adults' stronger foundational symbolic numerical skills. Therefore, the use of additional measures of inhibitory control, particularly those measuring inhibition of a motor response (e.g. go/no-go / stop signal task), may be particularly useful in highlighting group differences between younger and older adults due to a specific deficit of inhibiting an overt motor response in older age (Kramer et al., 1994). A battery of inhibition tasks yielding interference effects for a variety of inhibitory functions would therefore allow more detailed investigation of which functions specifically may be involved in foundational non-symbolic numerical skills.

9.4.4 The age-old problem of ageing research

Research investigating the effects of ageing always faces the challenge of cohort effects. Where researchers intend to compare cognition in younger and older adults, in the vast majority of cases cohort studies are the only option. Such a comparison may lead to cohort effects: group differences due to factors other than cognitive ageing (e.g. educational differences: Geary & Lin, 1998). The research presented within the thesis aimed to address such concerns where possible, for example by controlling for education, mathematical, and verbal abilities. Further, regression analyses were applied to predict foundational numerical abilities in ageing, providing evidence that enhanced symbolic abilities were due to cognitive ageing over and above the contribution of superior mathematical achievement. Finally, recruitment to a study undertaken on a university campus may attract the highest performing older adults, whereas those recruiting participants from care homes may lead to an over-representation of cognitive decline in older age (Hedden & Gabrieli, 2004). As far as possible, the research compared groups of younger and older adults with similar years in formal education, whilst also excluding older adults presenting evidence of cognitive decline. Ideally, longitudinal studies would aim to track the trajectory of numerical cognition in ageing within the same cohort over a period of decades (as with population based samples). However, the feasibility, cost, and difficulties inherent in such studies are clear.

9.4.5 Pathological ageing

The thesis presents a perspective of stable foundational numerical abilities in healthy ageing. Such findings could therefore be applied to pathological ageing, such as in Alzheimer's disease (AD) (Delazer et al., 2006; Duverne et al., 2003; Girelli et al., 1999; Kaufmann et al., 2002; Khodarahimi & Rasti, 2011; Maylor et al., 2005). As numerical cognition is derived from the parietal lobes (Piazza & Izard, 2009; Roitman et al., 2012), and these cortical regions undergo significant atrophy in early and potentially in preclinical AD (Bruner & Jacobs, 2013; Jacobs et al., 2011; Jacobs et al., 2012), future research would benefit from comparing foundational numerical skills between healthy ageing and AD. As foundational non-symbolic skills are preserved and symbolic skills enhanced in healthy ageing, declined foundational abilities may provide a specific indicator for AD. Indeed, when compared to healthy ageing, older adults with AD demonstrate poorer calculation skills (Cappelletti, Butterworth, & Kopelman, 2012), reduced arithmetic fact retrieval (Duverne et al., 2003), as well as declined counting acuity (Delazer et al., 2006). Deteriorated foundational numerical abilities in AD could potentially aid in the early detection of the disease, with a timely diagnosis vital for effective treatment and better outcomes (Salthouse, 2009). In particular, the non-symbolic comparison task applied throughout the thesis (Halberda et al., 2008) has been utilised across populations of varying ability, demonstrating its potential for use in clinical populations. Several cognitive functions shown to significantly decline in AD, such as executive functions, problem solving, and memory (e.g. Lafleche & Albert, 1995; Willis et al., 1998), also show some degree of decline in healthy ageing, often making a differentiation between healthy and pathological ageing difficult. The discovery of preserved numerical abilities in healthy ageing presented here therefore reflects previous research (Cappelletti et al., 2014, 2015), providing a stable trajectory of ability in healthy ageing for comparison with pathological ageing.

9.5 Final conclusions

With an ever increasing ageing population, what cognitive changes and stability to expect in older age becomes increasingly important, to both the scientific community and the ageing population. Research informs knowledge about what is normal in healthy ageing, but also what may signal pathological processes. The current thesis goes some way to exploring the impact of ageing on foundational numerical abilities, carefully applying a controlled design to investigate the impact of ageing on the number sense. However, future research will strengthen our broader understanding of what to expect, and what not to expect, with healthy ageing.

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11 Endnotes

[i] We would like to thank Nuerk, Weger, & Willmes for sharing their symbolic comparison paradigm with us.

[ii] Participant numbers are unequal due to extra data collection for a research article

[iii] We would like to extend our thanks to Sarah Clayton, Camilla Gilmore, and Matthew Inglis at Loughborough University for suggesting these analyses and sharing the software required for calculating convex hulls.