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**The differential recruitment of short-term memory and executive functions during time, number and length perception: An individual differences approach.**

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18 **The differential recruitment of short-term memory and executive functions during time, number**  
19 **and length perception: An individual differences approach.**  
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37 Running head: Memory, executive function and magnitude processing.  
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**Abstract**

Developmental, behavioural and neurological similarities in the processing of different magnitudes (time, number, space) support the existence of a common magnitude processing system (e.g. ATOM; Bueti & Walsh, 2009; Walsh, 2003). It is however unclear whether the recruitment of wider cognitive resources (STM and executive function) during magnitude processing is similar across magnitude domains or domain specific. The current study used an individual differences approach to examine the relationship between STM, executive function and magnitude processing. In two experiments, participants completed number, length and duration bisection tasks to assess magnitude processing and tasks which have been shown to assess STM span and the four key executive component processes identified by Miyake et al. (2000) and Fisk and Sharp (2004) (shifting, inhibition, updating and access). The results suggest that the recruitment of STM and executive resources differed for the different magnitude domains. Duration perception was associated with access, inhibition and STM span. Length processing was associated with updating and number processing was associated with access to semantic memory. For duration and length, greater difficulty in the magnitude judgement task resulted in more relationships to STM and executive function. It is suggested that duration perception may be more demanding of STM and executive resources because it is represented sequentially, unlike length and number which can be represented non-sequentially.

Key words: magnitude, memory, executive function, duration, number.

## Introduction

A Theory of Magnitude (ATOM; Buetti & Walsh, 2009; Walsh, 2003) suggests that different domains of magnitude (e.g. time, space, numerosity) share a common neural processing system located in the parietal cortex. There is considerable support for this suggestion. From a young age humans are able to make judgments about magnitude (Droit-Volet, Clement, & Fayol, 2003; Droit-Volet, Tourret & Wearden, 2004; Feigenson, 2007). This ability develops comparably, regardless of the magnitude being judged (e.g. duration, number or length), and conforms to Weber's Law (see Dehaene & Brannon, 2011; Dormal & Pesanti, 2012; Droit-Volet, et al., 2003) suggesting a shared developmental trajectory (Droit-Volet et al., 2003; Feigenson, 2007).

Studies examining the effect of simultaneous processing of multiple magnitudes offer further support for common processing. These studies typically adopt an interference paradigm in which participants are required to make judgements about magnitude A (e.g. duration) whilst experiencing task irrelevant information from another magnitude B (e.g. number). Interference from the task-irrelevant magnitude is taken as evidence for a shared processing system for different magnitudes. Task irrelevant numerical information has been found to interfere with temporal judgements (e.g. Coull, Charras, Donadieu, Droit-Volet & Vidal, 2015; Dormal, Seron & Pesenti, 2006; Oliveri, 2008; Xuan, Zhang, He & Chen, 2007). For example, larger numerical representations (symbolic or non-symbolic) are judged as lasting for longer than smaller representations (e.g. Oliveri, 2008). Similarly, task irrelevant spatial information has been found to interfere with concurrent temporal processing in children and adults (Bottini & Casasanto, 2010; 2013; Casasanto & Boroditsky, 2008; Xuan et al., 2007). For example, small surface areas were perceived as being presented for a shorter amount of time than large surface areas (Xuan et al., 2007).

Neuro-imaging (Cohen Kadosh et al., 2008), neuropsychological (e.g. Dehaene & Cohen, 1997; Irving-Bell, Small & Cowey, 1999; Koch, Oliveri, & Caltagirone, 2009), TMS (Knops, Nuerk, Sparing, Foltys & Willmes, 2006) and single unit recording (Tudusciuc & Nieder, 2007) studies show evidence for a common magnitude processing system located in the parietal cortex (see Buetti & Walsh, 2009; Dormal & Pesanti, 2012 for detailed discussion). Neuroimaging studies reveal parietal activation when processing numerosity (Dehaene, Piazza, Pinel & Cohen, 2003), duration (Pouthas et al., 2005) and space/length (Pinel et al., 2004). Critically, overlapping activation in the superior parietal lobule and the intraparietal sulcus has also been reported when processing numerosity and spatial representations (Kaufmann et al., 2008). Neuropsychological studies show that parietal damage results in impaired temporal (Koch et al., 2009), numerical (Dehaene & Cohen, 1997) and spatial (Irving-Bell et al., 1999) discrimination. In addition to activation common to all magnitudes, there is also emerging evidence of activation unique to individual magnitudes (Tudusciuc & Nieder, 2009). In a single unit recording study of monkeys performing length and number discrimination tasks, Tudusciuc and Nieder (2009) observed evidence of three groups of neurons; one uniquely encoding for length, another uniquely encoding for number and a third group which encode both length and number. Within any general magnitude processing system in the parietal cortex there may, therefore, be magnitude specific neurons.

Although well supported, ATOM does not specify how wider cognitive resources such as short-term memory (STM) and executive functions are recruited during magnitude processing (Dormal & Pesanti, 2012). Specifically, it is unclear whether the processing of different domains of

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3 magnitude differentially require attentional and memory resources. The current paper aimed to  
4 explore this. Behavioural evidence suggests that different domains of magnitude may use different  
5 attentional and memory resources. When simultaneously processing two magnitude domains (e.g.  
6 time and number), the interference is asymmetrical; timing is disrupted by concurrent numerical and  
7 spatial processing however numerical (Dormal & Pesanti, 2013; Droit-Volet et al., 2003) and spatial  
8 processing (Bottini & Casasanto, 2013; Dormal & Pesanti, 2013) are not disrupted by concurrent  
9 timing. This asymmetry may occur because processing duration is more demanding than other  
10 magnitudes (Droit-Volet et al., 2003), or less automatic (Dormal & Pesanti, 2013), perhaps requiring  
11 greater attention or working memory capacity during processing.  
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15 Memory representations of duration also appear to decay differently from those of other  
16 magnitude domains. This is illustrated by the phenomenon of subjective shortening, in which the  
17 subjective duration of a stimulus is decreased as its period of retention is increased (Wearden, Parry  
18 & Stamp, 2002). Subjective shortening occurs with durations in animals (Spetch & Wilkie, 1983) and  
19 humans (Wearden & Culpin 1995; Wearden & Ferrara, 1993; Wearden et al., 2002). Attempts to  
20 replicate this effect in animals with numerosity (Roberts, Macuda & Brodbeck, 1995), and humans  
21 with length (Wearden et al., 2002) have however failed to produce clear evidence for subjective  
22 shortening outside of the temporal domain, indicating that it may be a unique quality of temporal  
23 information. Similarly, studies exploring the long-term retention of magnitude also suggest  
24 differences between temporal, spatial and pitch processing (Ogden, Wearden & Jones, 2008, 2010;  
25 Ogden & Jones, 2011). Ogden et al. (2008, 2010) demonstrated that retaining multiple different  
26 auditory durations, over a period of delay, led to systematic distortion (shortening or lengthening) of  
27 the memory representation of the first encoded duration. Later studies failed to replicate this  
28 systematic distortion effect when multiple different pitches or lengths of line were retained over a  
29 delay (Ogden & Jones, 2011).  
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35 Developmentally, memory for duration also appears to differ from memory for other  
36 magnitude domains (McCormack, Brown, Smith & Brock, 2004). Differences in the children's and  
37 adults' performance on some temporal tasks have historically been explained by the suggestion that  
38 children's memory systems systematically distort representations of duration, making them shorter.  
39 This shortening effect disappears by adulthood (Droit-Volet, Clement & Wearden, 2001; McCormack,  
40 Brown, Maylor, Derby & Green, 1999). This distortion is not, however, evident when children are  
41 processing pitch (i.e. identifying a previously learned pitch from a series of higher and lower pitches).  
42 Similarly, distortions in memory representations of duration information present in elderly  
43 participants are not replicated when the same participants are judging pitch (McCormack, Brown,  
44 Maylor, Richardson & Darby, 2002). Collectively these studies indicate that the way in which  
45 duration representations are encoded and/or retained in memory is qualitatively different from the  
46 way in which other domains of magnitude are encoded and stored. This may be because the  
47 maintenance of duration requires different attentional, working and short-term memory resources  
48 than the maintenance of other domains of magnitude.  
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53 One way to examine whether the attention and memory demands associated with duration  
54 processing differ from those associated with other magnitude processing is to explore the  
55 relationships between performance on tasks assessing magnitude processing and tasks assessing  
56 general cognitive function (i.e. STM and executive function). Such individual differences approaches  
57 have proved fruitful in understanding the wider cognitive demands of timing in adults (Ogden et al.,  
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2014), how these demands change developmentally (Droit-Volet & Zelanti, 2013; Zelanti & Droit-Volet, 2011, 2012) and how they differ on different timing tasks (Droit-Volet & Zelanti, 2013; Zelanti & Droit-Volet, 2011, 2012; Ogden et al., 2014). From this, and other work, it is clear that duration perception is influenced by STM, (e.g. Baudouin, Vanneste, Pouthas, & Isingrini, 2006; Droit-Volet, Delgado & Rattat 2006; Droit-Volet & Zelanti, 2013; Zelanti & Droit-Volet, 2011, 2012; Franssen & Vandierendonck, 2002; Perbal, Droit-Volet, Isingrini & Pouthas, 2002; Ulbrich, Chuzan, Fink, & Wittmann, 2007) and executive function (Brown, 2006, 2014; Brown, Collier, & Night, 2013; Droit-Volet & Zelanti, 2013, Fortin, Schweickert, Gaudreault, & Viau-Quesnel, 2010; Mioni, Mattalia, & Stablum, 2013; Ogden, Salominaite, Jones, Fisk, & Montgomery, 2011; Ogden et al. 2014; Wearden, Wearden, & Rabbitt, 1997; Zelanti & Droit-Volet, 2011, 2012) with better STM and executive capacity being associated with better duration sensitivity.

We therefore used an individual differences approach to examine the relationships between STM and executive function task performance and performance on duration, number and length bisection tasks. Theoretical models of executive function have fractionated the central executive into four components. Miyake et al. (2000) identified updating, referring to an individual's ability to monitor incoming information and to update the contents of working memory accordingly, inhibition, referring to an individual's ability to inhibit a dominant or automatic response when it is inappropriate, and switching, referring to an individual's ability to switch their attention between different tasks or different elements of the same task. Fisk and Sharp (2004) added access to semantic memory, referring to the efficiency with which an individual accesses semantic memory content. Participants were asked to complete a verbal and spatial STM span task, verbal and spatial updating tasks, random number generation (RNG Baddeley, 1998) to assess inhibition, the number-letter task (adapted from Rogers & Monsell, 1995) to assess switching and the Chicago Word Fluency Test to assess access to semantic memory. Participants also completed duration, number and length bisection tasks. [The relationships between performance on the different tasks were explored. Previous research suggests that greater STM and executive function capacity is associated with greater sensitivity on timing tasks. We would therefore expect better STM and executive function to be associated with greater magnitude sensitivity.](#)

## Experiment 1

### Method

#### *Participants*

Sixty Liverpool John Moores University students (mean age = 21.32, SD = 1.61, 22 male) were paid £10 for participating. Payment was not contingent on performance.

#### *Apparatus*

An IBM compatible computer running Microsoft Windows and a 17" LCD monitor were used to present and record experimental events. For the magnitude bisection tasks, stimulus presentation and recording of keyboard responses were controlled via E-Prime version 2.0 (Psychology Software Tools, Inc., Pittsburgh, PA). The RNG task, the number-letter task, the letter/spatial span tasks and the letter/spatial updating tasks were programmed in MS-DOS. Responses on the CWFT task were recorded with a pen and answer sheet and timed with a stop-watch.



### *Procedure*

All participants were tested in a single experimental session lasting approximately 90 minutes and completed a total of 10 tasks presented in a random order for each participant (although the span tasks always preceded the updating tasks). Magnitude discrimination was assessed using three bisection tasks; duration, numerosity and length. STM span and updating ability was assessed using letter and spatial span and updating tasks. Inhibition was assessed using random number generation (RNG, Baddeley, 1998). Switching was assessed using the number letter task (adapted from Rogers & Monsell, 1995). Access was assessed with the Chicago Word Fluency Test (Thurstone & Thurstone, 1938).

### *Bisection Tasks*

Participants completed three separate bisection tasks; duration, number and length. At the start of each task participants were informed that they needed to learn two standard magnitudes (duration: short/long; number: few/many; length: short/long) and then decide whether subsequently presented comparison stimuli were more similar to the short/few or long/many standard. Participants were instructed not to count during all tasks (Rattat & Droit-Volet, 2012).

*Duration bisection:* At the start of the experiment participants were presented with four examples each of the short standard (600ms) and four examples of the long standard (1,200 ms). The standard was presented as a blue circle (7cm diameter) on a white background. A delay, the duration of which was drawn at random from a uniform distribution ranging from 500-1,000 ms, was interposed between each presentation of the standards. Following the presentation of the standards, comparison durations were presented and participants were instructed to indicate whether each comparison was more similar to the short or long standard by pressing the S key on the keyboard for short and the L key for long. Each block contained 11 comparison stimuli; 600ms (presented three times), 700ms, 800ms, 900ms, 1,000ms, 1,100ms and 1,200ms (presented three times), each was presented in a random order. Five blocks of comparisons were completed by each participant giving a total of 55 trials. No performance feedback was provided.

*Number bisection:* the procedure was identical to that used for duration bisection apart from the stimuli employed as standards and comparisons. Standards and comparisons were presented as blue circles, whose spatial arrangement was randomly allocated on a 12 x 12 square grid of 144 possible locations. Standards were labelled as "few" (six items in an array) and "many" (12 items in an array). The surface area of the standards was controlled so that the few and many shared the same overall surface area (e.g. 6 circles 1.41 cm in diameter vs 12 circles 1cm in diameter). Comparisons were presented as arrays of 6, 7, 8, 9, 10, 11 and 12 items. The surface area of each comparison stimulus was the average of the total surface area during standard presentation (e.g. 1.24 cm in diameter). Participants responded by pressing the F key for few and the M key for many. Stimuli were presented on the screen for 1500 ms and following this the participants responded.

*Length bisection:* the procedure was identical to that used in the number task however standard and comparisons were presented in the form of a horizontal blue line (0.25 cm wide) on a white background randomly positioned on a 10 x 10 square grid of 100 possible locations around the centre of the computer. The short standard was 6cm in length and the long standard was 12 cm in length. Comparison stimuli were 6, 7, 8, 9, 10, 11 and 12 cm in length.

### Cognitive Tests

#### *Letter Span: Verbal STM Span (Adapted from Fisk & Sharpe, 2004)*

Consonants were presented sequentially on the computer screen each for 1.25 s. The participants' task was to then recall the letters in order that they were presented. The task began with three sets of two letters and then increased in difficulty to three, four, five etc. until the participant failed on two or more of the three trials. Letter span 'n' is defined as the maximum number of letters recalled in serial order subject to the requirement that this level is achieved in at least two of the three trials for that particular level.

#### *Letter Updating (adapted from Morris & Jones, 1990)*

The participant's letter span, 'n', was first determined in the letter span version of the task. In the updating version of the task, the participant was then presented with a random sequence of between  $n$  and  $n + 6$  consonants on the computer screen. There were twenty-four separate trials in total, with six trials at each of the four randomly presented list lengths:  $n$ ,  $n + 2$ ,  $n + 4$  and  $n + 6$ . For each trial the participant was unaware of the number of consonants to be presented. The participants' task was to always recall the most recent 'n' consonants in the order that they were presented. A composite score of updating was calculated by computing the average number correct for each serial position across the six trials at each separate list length. These scores were then averaged over list length and serial position to generate the composite updating score.

#### *Spatial Span: Spatial STM Span (adapted from Fisk & Sharpe, 2004).*

Participants were presented with a pattern that consisted of 12 blank squares on the computer screen set out in a Corsi-type layout and were informed that some of the squares would be filled with a series of Xs one at a time. Participants were asked to remember the position and order in which each of the cells were highlighted and then write down the positions of all of the cells in the order that they were filled. The task began with three sets of two cells being highlighted, and then increased in difficulty to three, four, five etc. until the participant failed on two or more of the three trials. Spatial span 'n' is defined as the maximum number of cells recalled in serial order subject to the requirement that this level is achieved in at least two of the three trials for that particular level.

#### *Spatial Updating (adapted from Morris & Jones, 1990)*

The spatial updating task required participants to recall the cells that were highlighted sequentially, one cell at a time, in a Corsi-style layout. As with the letter updating task, the participant's span, 'n', was determined. In the updating task, the participant was then presented with a random sequence of between  $n$  and  $n + 6$  cells highlighted on a computer screen. Twenty-four such sequences were presented with six trials at each of the four randomly presented list lengths:  $n$ ,  $n + 2$ ,  $n + 4$  and  $n + 6$ . In each case the task was always to recall the most recent 'n' cells in the order in which they were highlighted. A single composite updating score was calculated using the same method outlines for the consonant updating version of the task.

#### *Random Number Generation (RNG; Baddeley, 1998): Inhibition*

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3 A computer display and concurrent auditory signal was used to pace participants' responses.  
4 Participants were asked to speak aloud a number in the range of 0-9 inclusive every time the signal  
5 was presented. Each participant was told to avoid repeating the same sequence of numbers, to  
6 avoid producing natural sequences (e.g. 1, 2, 3), and to try to speak each number with the same  
7 overall frequency. Each participant attempted to produce one set of 100 numbers at a rate of 1  
8 number every second. Four separate scores were then calculated corresponding to the number of  
9 numerically ordered pairs, the number of times that the same number pair was repeated, a  
10 "redundancy" score measuring the extent to which all numbers were produced equally often and  
11 the overall number of items that were produced. In the first three cases, higher scores indicate poor  
12 performance; in the fourth the opposite is true. Each of the four separate scores were standardised  
13 and a single score of randomness was calculated by summing the three scores for redundancy,  
14 repeat and alpha and then subtracting the score for the overall number of items produced. [This](#)  
15 [score was then reverse scored so that a higher score on this task indicated better inhibitory](#)  
16 [performance.](#)  
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### 21 *Number-letter Task: Switching*

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23 Adapted from Rogers and Monsell (1995) and Miyake et al. (2000), in this task number-letter pairs  
24 (e.g. J6) were presented one at a time in one of four quadrants on a computer screen. If the number-  
25 letter pair appeared in one of two top quadrants, the participant had to attend to the letter and  
26 respond as to whether it was a vowel or a consonant. If it was in the one of the two bottom  
27 quadrants, the participant was required to attend to the number and respond to whether it was odd  
28 or even. Responses were made via pressing the key "Z" for consonant and odd and the key "/" for  
29 vowel and even. The task started with a practice version of three sets. The target was presented in  
30 the top half of the screen for 12 trials, then the bottom half for 12 trials and then in a clockwise  
31 rotation around all four quadrants for a further 12 trials. The main task then followed the same  
32 structure but with 64 trials in each block. The third block of both the practice and main task required  
33 participants to switch between making letter and number judgements, meaning that the first two  
34 blocks required no switching, were as the third block did. The switch cost was then calculated as the  
35 difference between the average reaction times of the third block and the averages of the first two  
36 blocks.  
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### 41 *Chicago Word Fluency Test: Access to Semantic Memory* (adapted from Thurstone & Thurstone, 42 1938)

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44 Participants were given four minutes during which their task was to write down as many four-letter  
45 words beginning with the letter "C" as they could, excluding any place names, people's names or  
46 plurals. As plurals were not allowed, words such as "cars" and any repetitions of words were  
47 excluded. Participants wrote their responses on an answer sheet provided for this purpose and  
48 scores were calculated as the total number of appropriate words produced.  
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## 51 **Results**

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54 Figure 1 about here

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56 Figure 1 shows psychophysical functions for duration, number and length. Examination of  
57 Figure 1 suggests that responding was orderly, with the proportion of long responses increasing  
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3 linearly with the magnitude of the comparison. The function for duration discrimination appeared  
4 flatter than the number and length functions, suggesting less sensitive performance. A repeated  
5 measures ANOVA with within-subject factors of type of magnitude (duration, number, length) and  
6 comparison stimulus showed significant main effects of comparison stimulus  $F(6, 360) = 965.35, p$   
7  $<.001 \eta_p^2 = .94$  and magnitude type  $F(2, 120) = 12.45, p <.001 \eta_p^2 = .18$ . There was also a significant  
8 interaction between magnitude type and comparison stimulus value  $F(12, 720) = 7.79, p <.001$   
9  $\eta_p^2 = .12$ . Bonferroni corrected post-hoc tests showed that responding in the duration discrimination  
10 task differed significantly from that in the number and length discrimination tasks ( $p <.001$ ). There  
11 was no significant difference between number and length discrimination ( $p = .99$ ).  
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14  
15 To explore the relationship between bisection performance and STM and executive function  
16 we calculated the bisection point (BP) for duration, number and length for each participant. The BP  
17 is the comparison stimulus giving rise to  $p(\text{long/many}) = .50$ . The bisection points were determined  
18 by a method similar to that introduced by Maricq, Roberts, and Church (1981), and used in a number  
19 of articles on bisection in humans since (Wearden, 1991; Wearden & Ferrara, 1995). Linear  
20 regression was performed on points from the steepest part of the psychophysical function, and this  
21 was used to calculate the bisection point, the stimulus value giving rise to 50% long/many responses.  
22 Next, the difference limen was calculated, being half the difference between the values giving rise to  
23 75% and 25% long/many responses. The Weber ratio, an index of judgment sensitivity, was then  
24 derived by dividing the difference limen by the bisection point. The higher the WR, the flatter the  
25 psychophysical function, and the lower the sensitivity to the different values of the stimuli tested.  
26 Analysis of the relationship between WRs and difference limen showed a strong positive correlation  
27 for duration ( $r = .94, p <.001$ ), numerosity ( $r = .96, p <.001$ ), and length ( $r = .96, p <.001$ ). For brevity,  
28 we only report the WR in our analysis. There are a number of different methods of calculating the  
29 bisection point from a psychophysical function, but when Wearden and Ferrara (1995) compared  
30 some of them results were found to be almost identical.  
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36 A repeated measures ANOVA showed significant differences in the bisection points of the  
37 three magnitudes  $F(2, 118) = 12.73, p <.001 \eta_p^2 = .17$ . Bisection points were significantly greater for  
38 duration ( $M = 9.18, SD = 1.71$ ) than number ( $M = 8.34, SD = .85$ ) and length ( $M = 8.27, SD = .77$ ) ( $p$   
39  $<.001$ ). There was no significant difference in BP for number and length ( $p = .99$ ). The same analysis  
40 performed on the Weber Ratios also showed a significant effect of magnitude  $F(2, 118) = 32.67, p$   
41  $<.001 \eta_p^2 = .35$ . Weber Ratios were significantly greater for duration ( $M = .16, SD = .09$ ) than number  
42 ( $M = .09, SD = .06$ ) and length ( $M = .07, SD = .02$ ) ( $p <.001$ ). There was no significant difference in  
43 WR for number and length ( $p = .37$ ).  
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46 Spearman's correlation coefficient was then used to examine the relationship between STM  
47 and executive capacity and magnitude discrimination. Table 1 shows correlation coefficients and  $p$   
48 values for the relationships between STM, executive functions and magnitude bisection.  
49 Examination of Table 1 suggests that the discrimination of duration, number and length differentially  
50 related to executive and STM capacity. Duration discrimination WRs were negatively related to  
51 access to semantic memory (CWFT), STM Span (letters) and inhibition (RNG). Better STM, access and  
52 inhibitory capacity were therefore all related to improved temporal sensitivity. Duration BP was  
53 positive related to inhibition, therefore greater inhibitory capacity was associated with a higher BP.  
54 Number discrimination WRs were negatively related to access to semantic memory. Number BP did  
55 not relate to executive or STM capacity. There were no relationships between any measure of length  
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3 discrimination and executive or STM capacity. Taken together these results suggest that duration  
4 discrimination is more strongly related to STM and executive capacity than either length or number  
5 discrimination.  
6

## 7 8 **Discussion**

9  
10 The results of Experiment 1 suggest that the nature of the relationship between STM and  
11 executive function task performance and magnitude bisection performance is dependent on the  
12 domain of the magnitude being judged. Duration bisection performance was associated with  
13 different executive functions to length or number bisection. Duration bisection performance was  
14 associated with STM letter span, inhibition and access to semantic memory. Better access, letter  
15 span and inhibition were associated with increased sensitivity to time. In addition, poorer inhibition  
16 was associated with a reduction in bisection point value. Number bisection was only associated with  
17 access to semantic memory, with better access being associated with an increase in bisection point  
18 and lower sensitivity to numerosity. Length bisection performance was not associated with any  
19 measures of STM or executive function.  
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23 These findings suggest that when the ratio between the stimuli being judged is constant  
24 across domains (i.e. the S:L ratio is the same for all domains), there is domain specific recruitment of  
25 STM and executive functions. Concluding that this indicates that different domains of magnitude  
26 have stronger relationships with particular STM and executive resources may however be premature  
27 because of the relative differences in task difficulty between the duration, number and length tasks.  
28 Although all three tasks had the same S:L ratio (1:2), performance was only equivalent in the length  
29 and number tasks. Participants demonstrated relatively less sensitivity to magnitude on the duration  
30 task, as evidenced by the flatter psychophysical function and greater WR. This disparity in difficulty  
31 may have contributed towards the greater number of associations between duration bisection and  
32 STM and executive function than length and number bisection.  
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36 Experiment 2 was therefore conducted to establish whether the differences observed in  
37 Experiment 1 reflect domain based differences in wider cognitive resource recruitment during  
38 magnitude perception or the effect of greater task difficulty. Experiment 2 was a replication of  
39 Experiment 1: however, the difficulty of the discrimination judgement was altered. In Experiment 1,  
40 performance on the duration discrimination task indicated that the task was more difficult than the  
41 number or length discrimination task. To establish whether this disparity contributed to the results,  
42 in Experiment 2 the difficulty of the duration discrimination task was relatively reduced by increasing  
43 the S:L ratio to 1:3 and the difficulty of the length and number discrimination tasks were relatively  
44 *increased* by reducing the S:L/few:many ratio. Wearden et al. (2002) used the same approach in  
45 Experiment 3 of their paper to understand the effects of task difficulty on subjective shortening. *In  
46 addition, we also note that although in Experiment 1, participants were instructed not to count  
47 during the bisection tasks, it is possible that they did so anyway, and that this may have affected  
48 performance on the numerosity task. In Experiment 2, further safeguards against counting were  
49 introduced by 1) increasing the set size in the numerosity task to 24-30 items and 2) reducing the  
50 presentation duration from 1,500ms to 500ms.*  
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## 55 **Experiment 2**

### 56 *Participants*

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3 Fifty-eight Liverpool John Moores University students (mean age = 23.00 years, SD = 4.94 years, 20  
4 males) were paid £10 for participating. Payment was not contingent on performance.  
5

#### 6 Apparatus

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8 As in Experiment 1.  
9

#### 10 Procedure

11  
12 The general procedure remained the same as in Experiment 1 with the exception of the stimulus  
13 values used in the bisection tasks.  
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16 *Duration bisection:* The durations used changed from Experiment 1 to make the task easier. The  
17 short standard was 400ms and the long standard was 1200ms. Comparison values were 400, 533,  
18 667, 800, 933, 1067, 1200ms. All other procedural details remained the same.  
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21 *Number bisection:* The quantities used and the stimulus presentation duration changed from  
22 Experiment 1 to make the task harder. The few standard was 24 and the many standard was 30.  
23 Comparison values were therefore 24, 25, 26, 27, 28, 29, 30. Stimulus presentation duration was  
24 reduced to 500ms. All other procedural details remained the same.  
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27 *Length bisection:* The lengths used and the stimulus presentation duration changed to from  
28 Experiment 1 make the task harder. The short standard was 60mm and the long standard was 66mm.  
29 Comparison values were therefore 60, 61, 62, 63, 64, 65, 66 mm. Stimulus presentation duration was  
30 reduced to 500ms. All other procedural details remained the same.  
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#### 32 Results

33  
34 Figure 2 here  
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36  
37 Figure 2 shows psychophysical functions for duration, number and length. Examination of  
38 Figure 2 suggests that responding was orderly with the proportion of long responses increasing  
39 linearly with the magnitude of the comparison. The function for duration discrimination appeared to  
40 be steeper than the number and length functions suggesting more sensitive performance. A  
41 repeated measures ANOVA with within-subject factors of type of magnitude (duration, number,  
42 length) and comparison stimulus showed significant main effects of comparison stimulus  $F(6, 342) =$   
43  $415.10, p < .001 \eta_p^2 = .88$  and magnitude  $F(2, 114) = 3.24, p < .05 \eta_p^2 = .06$ . There was also a significant  
44 interaction between magnitude type and comparison stimulus  $F(12, 684) = 19.24, p < .001 \eta_p^2 = .25$ .  
45 Bonferroni corrected post-hoc tests showed that responding in the duration discrimination task  
46 differed significantly from that in the number and length discrimination tasks ( $p < .05$ ), which  
47 themselves did not differ ( $p = .18$ ).  
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51 To enable meaningful comparison of the BP and WR for duration, number and length,  
52 comparison values were normalised across experiments to 1, 2, 3, 4, 5, 6, and 7. These comparison  
53 values were then used in the linear regression to produce BP and WR values using the same method  
54 described in Experiment 1. A repeated measures ANOVA showed no significant difference in the  
55 bisection points for duration ( $M = 3.56, SD = .61$ ) than number ( $M = 4.01, SD = .94$ ) and length ( $M =$   
56  $3.86, SD = 1.30$ ). The same analysis performed on the Weber Ratios showed a significant effect of  
57 magnitude  $F(2, 114) = 4.58, p = .01 \eta_p^2 = .08$ . Weber Ratios were significantly lower for duration ( $M$   
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3 = .24, SD = .09) than number (M = .35, SD = .20) and length (M = .39, SD = .36) ( $p < .05$ ). There was no  
4 significant difference in WR for number and length ( $p = .99$ ). Sensitivity was therefore significantly  
5 greater for duration than for length and number.  
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8 Spearman's correlation was then used to examine the relationship between STM and  
9 executive capacity and magnitude discrimination. Table 2 shows correlation coefficients and p values  
10 for the relationships between magnitude discrimination (BP and WR) and STM and executive  
11 function. For this analysis, BP and WR were re-computed using the stimulus values used in the actual  
12 experiment. Examination of Table 2 suggests that there were no significant relationships between  
13 executive function or STM capacity and duration discrimination (BP, WR). For number discrimination,  
14 there was a significant negative relationship between number WR and access. There were no other  
15 significant relationships between number discrimination (BP or WR) and STM capacity or executive  
16 function. For length discrimination, there were no relationships between STM capacity, access,  
17 inhibition or switching. There were however significant negative relationships between measures of  
18 updating and length BP and WR.  
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21  
22 Table 2 about here  
23

## 24 Discussion

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26 Changing the S:L ratio had the desired effect on task performance; magnitude sensitivity was  
27 significantly greater for duration than length and number. Length and number performance  
28 remained about equal, as in Experiment 1. As expected, changing the relative difficulty of the  
29 bisection tasks affected the extent to which their performance correlated with STM and executive  
30 task performance. Increasing the S:L ratio of the duration bisection task, making it *less* difficult than  
31 in Experiment 1, reduced the extent to which duration bisection performance correlated with STM  
32 and executive task performance. In Experiment 1, duration bisection performance was positively  
33 associated with verbal STM, inhibition and access task performance. In Experiment 2 however, there  
34 were no associations between duration bisection and STM or executive performance. Increasing the  
35 difficulty of the numerosity bisection task (by decreasing the S:L ratio) did not affect its performance  
36 associations with STM or executive measure, access to semantic memory remained the only  
37 association. Indeed, despite the increase in stimulus set size, and the reduction in presentation  
38 duration, the direction and strength of the relationship between numerosity WR and access to  
39 semantic memory remained the same. This perhaps suggests that similar strategies were used in  
40 Experiment 1 and 2. Increasing the difficulty of the length discrimination task increased the  
41 associations between STM and executive function task performance and length bisection  
42 performance. Better updating performance was associated with a reduction in bisection point and  
43 an improvement in length sensitivity. There remained, however, no consistent pattern of association  
44 across the magnitude domains.  
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## 50 General Discussion

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52 ATOM suggests that different domains of magnitude (e.g. duration, length and numerosity)  
53 are processed in a common magnitude processing system (Buetti & Walsh, 2009; Walsh, 2003).  
54 Developmental, behavioural and neurological research offers support for this suggestion. ATOM  
55 does not however make specific suggestions about the role of "general cognitive processes" such as  
56 STM, WM and executive function in the processing of different magnitude domains (Dormal &  
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3 Pesanti, 2012). Consequently, it is unclear whether these general resources are associated with  
4 magnitude perception in domain-specific or domain-general ways. This study examined this using an  
5 individual differences approach. The findings suggest that the relationship between magnitude  
6 bisection performance and STM and executive function performance is complex and varies  
7 according to the magnitude domain being judged and the difficulty of the task.  
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10 When relatively less difficult, length judgements were not related to STM or executive  
11 function. When relatively more difficult, length judgement performance was only associated with  
12 updating, with more sensitive length judgments being associated with better updating. Regardless  
13 of task difficulty, number bisection performance was only associated with access to semantic  
14 memory with better access being associated with greater sensitivity. Critically, the length and  
15 number discrimination tasks were equally difficult tasks, yet, the aspects of STM and executive  
16 function that were related did not overlap. This is consistent with discrimination in these different  
17 domains of magnitude recruiting different aspects of executive functioning, regardless of task  
18 difficulty.  
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22 When relatively more difficult, duration sensitivity was associated with STM letter span,  
23 access to semantic memory and inhibition, with greater sensitivity being associated with better span,  
24 access and inhibition. When relatively less difficult however, duration performance was not  
25 associated with STM and executive performance. Although the difficulty of duration discrimination  
26 was never equivalent to the other domains, the harder duration task was the only discrimination  
27 task related to verbal STM and inhibition. This suggests that difficult duration discrimination tasks  
28 recruit qualitatively *different* memory and executive resources, rather than relying more heavily on  
29 the executive resources recruited by harder versions of the length and number discrimination tasks.  
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33 One obvious question is why, if processed by a common processing system, would different  
34 magnitudes differentially recruit different STM and executive resources? One suggestion is that  
35 although there is evidence for a common processing area in the parietal cortex, there is also  
36 evidence that within this, there are specific processing areas, which respond selectively for different  
37 magnitude domains (Tudusciuc & Nieder, 2009). In addition, other neural structures, particularly the  
38 SMA, maybe uniquely activated during the processing of duration (Coull et al., 2015). These  
39 differential outputs may therefore result in differential STM and executive requirements.  
40 Alternatively, as suggested by Dormal & Pesanti (2013), the processing of some magnitudes (e.g.  
41 number) may be more automatic than others (e.g. duration). Greater automaticity would reduce  
42 attentional demands, possibly resulting in differential recruitment of STM and executive resources  
43 for more and less automatic magnitude judgments. *It is important to note that the extent to which  
44 the processing of any magnitude is automatic may in part depend on the modality of presentation.  
45 Duration processing, for example, is more sensitive when the stimulus being timed is auditory than  
46 visual or vibrotactile (see Jones, Wells & Poliakoff, 2009 for a recent example). In children, more  
47 variable performance on visual than auditory timing tasks is thought to be in part due to the greater  
48 attentional and working memory demand of visual temporal processing (Zelanti & Droit-Volet, 2012).  
49 Therefore, it is possible that, in the current study, duration processing may have been “less  
50 automatic” because the stimuli were presented as visual rather than auditory stimuli. Similarly, it  
51 is possible that if number was presented as auditory stimuli (e.g. a series of tones) processing would  
52 become less automatic than when number is presented visually. Furthermore, these differences in  
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3 modality may influence how task performance relates to wider cognitive resources. Further research  
4 should clarify the effect of modality on the role of wider cognition in magnitude processing.  
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7 Fundamental properties of the magnitude itself may also drive differential STM and  
8 executive function requirements. Droit-Volet et al. (2008) articulate this point by distinguishing  
9 between sequential and non-sequential magnitude properties. Duration is sequential, in that there is  
10 a continuous flow of events which requires accumulation across time. Length and number, when  
11 presented as in the current experiments, are non-sequential, in that all stimuli are presented as a  
12 single discrete object. Droit-Volet et al. (2008) suggest that the sequential nature of duration may  
13 necessitate its processing to require different cognitive resources than other, static non-sequential,  
14 domains of magnitude. Particularly, they suggest that duration processing may be particularly  
15 demanding of attentional and working memory resources because the perceiver must maintain their  
16 attention on the stimulus over a longer period of time. This is supported by Coull et al.'s (2015) fMRI  
17 comparison of activation during sequential and non-sequential length and duration processing. Coull  
18 et al. (2015) suggest that the differential activation observed in the SMA, bilateral inferior frontal  
19 gyrus, left anterior insular, basal ganglia and bilateral middle/superior temporal cortex, during  
20 sequential and non-sequential processing perhaps reflects activity associated with WM and  
21 sequential processing in during duration processing, which is absent or reduced during other forms  
22 of static magnitude processing. In the current study, it is interesting to consider that verbal STM was  
23 *only* related to the processing of durations. It has been proposed that the auditory-verbal short-term  
24 store plays a crucial role in the retention of sequential information (see Baddeley, 2012 for a  
25 discussion). Consequently, the unique relationship between verbal STM and duration may reflect the  
26 intrinsically sequential nature of duration compared to the static nature of area and number.  
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32 The idea that sequentiality may be critical in establishing the similarities and differences  
33 between the processing and remembering of different magnitude domains is supported because  
34 certain phenomena associated with duration processing are only replicated in number and length  
35 processing when number and length are presented sequentially (i.e. the number of dots on a screen  
36 increases over time or the length of a line increases over time). For example, development  
37 differences in duration and length/number processing are present when number and length are  
38 presented non-sequentially, but absent when duration, number and length are presented  
39 sequentially (Droit-Volet et al., 2008). The phenomenon in which estimates of duration are  
40 lengthened when preceded by trains of clicks has also been found for length and number  
41 judgements, but only when the stimuli are presented sequentially; clicks had no effect when length  
42 and number were presented non-sequentially (Droit-Volet, 2010). Similarly, fear induced emotional  
43 arousal only affects length and number judgments in comparable ways to duration when the length  
44 and number stimuli are presented sequentially (Droit-Volet, 2013). Indeed, duration processing can  
45 be unaffected by the simultaneous processing of number or length if number and length are  
46 presented sequentially rather than non-sequentially (Lambrechts, Walsh, & Van Wassenhove, 2013).  
47 One explanation for these disparities is that comparable effects only manifest when the STM and  
48 attentional demands of the different magnitude domains are comparable, and that this only occurs  
49 when number and length are presented sequentially.  
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55 Sequentially presented magnitudes may require different memory and executive resources  
56 during the initial period of perception because an attentional focus must be maintained throughout  
57 the stimulus presentation. These increased attentional demands may also carry over into their  
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3 encoding and maintenance in memory. One possibility is that sequential stimuli require some form  
4 of “replaying” during encoding and recall, which would be demanding of cognitive resources,  
5 whereas static, non-sequential stimuli are simply encoded, recalled and maintained as static mental  
6 images, which may be relatively less demanding of cognitive resources. The vulnerability of duration  
7 memories to distortion or decay (Droit-Volet et al., 2001; Ogden et al., 2008, 2010, Ogden & Jones,  
8 2011; McCormack et al 1999, McCormack et al., 2002; Wearden et al., 2002) is supportive of these  
9 suggestions. However, although sequential processing may necessitate different STM and executive  
10 resources to non-sequential processing, it is unlikely to be the sole driver of the differences observed  
11 in this study. This is reflected in the absence of overlap in the STM and executive resources recruited  
12 during the non-sequentially presented length and number tasks despite them having equivalent  
13 difficulty.  
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18 A further factor which may influence STM and executive function recruitment during  
19 magnitude perception is the extent to which magnitude bisection performance is influenced by the  
20 use of long-term memory (LTM) representations of quantity. In the current studies, both number  
21 and duration bisection performance were related to access to semantic memory. For number  
22 bisection, this perhaps reflects the accessing of abstract numerical representations stored in LTM.  
23 For example, participants may have used their approximate number system (ANS Halberda &  
24 Feigenson, 2008), which is an imprecise, non-counting based, system for representing quantity, to  
25 aid bisection performance. A similar strategy may also have been used in the duration bisection  
26 tasks as it has previously been suggested that LTM representations of “key durations” e.g. 1 second  
27 may influence performance on temporal tasks (Ogden et al., 2014; Wearden, Jones, & Todd, 2006).  
28 To understand the extent to which long-term memory representations of magnitude are used in  
29 bisection tasks, further research should compare how wider cognitive resources relate to magnitude  
30 perception when counting is prevented (e.g. through sub-vocalisation) and reliance on the ANS/LTM  
31 is high with when counting is explicitly instructed and reliance on the ANS/LTM is relatively lower.  
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36 It should be noted that, although the present study highlights differential relationships  
37 between wider cognitive performance and duration, number and length perception, the correlations  
38 between performance on any of the tasks are only weak-moderate and  $p$  values were not corrected  
39 for multiple comparisons. It would therefore seem that whilst individual differences in magnitude  
40 perception are associated, in part, with individual differences in STM and executive function, other  
41 factors (e.g. decision thresholds, motivation, acuity of underlying magnitude representation) are also  
42 affecting performance.  
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45 A complicating factor in the present study was the effect of task difficulty. Correlations  
46 between STM and executive performance measures and duration perception indices depended on  
47 whether the duration task was easy (Experiment 2) or harder (Experiment 1). This does not mean  
48 that the resources recruited are different in the easy and more difficult case, only that the easy task  
49 is not sensitive to individual differences in STM and executive performance. For example, if a person  
50 is given one item to remember, then differences in the ability to this between individuals may be  
51 negligible and unrelated to other measures of memory. In contrast, if people are given 12 or 15  
52 items to remember, performance may be strongly related to more general memory capacity.  
53 However, in both cases memory is used: the basic underlying psychological process involved does  
54 not differ. The effect of task difficulty raises a number of methodological and theoretical problems.  
55 For one thing, there is the question of how task difficulty across different magnitude types should be  
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3 equated. In the case of bisection, should it be a measure of correct responses, the sensitivity of  
4 judgements (assessed by WR) or both? More problematical still are potential effects of task difficulty  
5 when different groups are compared, such as children of different ages, with or without an adult  
6 comparison group. Sensitivity to duration on bisection tasks increases with age in children (Droit-  
7 Volet & Wearden, 2001; McCormack et al., 1999), so different patterns of correlations at different  
8 ages between measures of cognitive performance and timing behaviour (as in Droit-Volet & Zelanti  
9 2013; Zelanti & Droit-Volet, 2001, 2012) may be in part due to changes in task difficulty. Further  
10 research should therefore focus on understanding precisely how task difficulty mediates the  
11 relationship between cognitive function and magnitude discrimination.  
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15 In conclusion, it is clear that there are some domain based differences in the recruitment of  
16 STM and executive function resources during magnitude bisection. Whilst this does not preclude the  
17 idea of a universal magnitude processing system, it suggests that this system may differentially  
18 recruit wider cognitive resources when processing different magnitude domains, either during the  
19 actual perceptual process, or downstream during memory encoding and the production of  
20 behavioural output. Duration perception appears to be more demanding of wider cognitive  
21 resources, perhaps because it is necessarily sequential in nature.  
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Figure list

Figure 1: Psychophysical functions from Experiment 1. Mean proportion of LONG/MANY responses plotted against the comparison value. Data are shown separately for the duration, number and length conditions.

Figure 2: Psychophysical functions from Experiment 2. Mean proportion of LONG/MANY responses plotted against the comparison value. Data are shown separately for the duration, number and length conditions.

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3 Table list  
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5 Table 1: Correlations between the measures of STM, executive function and the measures of  
6 magnitude perception.  
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8 Table 2: Correlations between the measures of STM, executive function and the measures of  
9 magnitude perception.  
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Figure 1: Psychophysical functions from Experiment 1. Mean proportion of LONG/MANY responses plotted against the comparison value. Data are shown separately for the duration, number and length conditions.

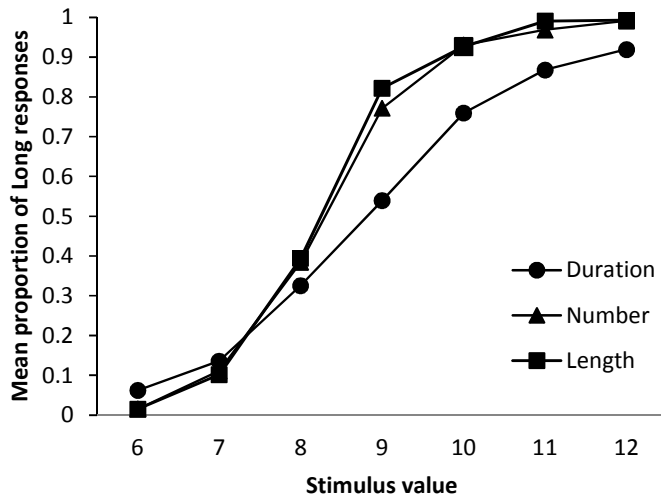


Figure 2: Psychophysical functions from Experiment 2. Mean proportion of LONG/MANY responses plotted against the comparison value. Data are shown separately for the duration, number and length conditions.

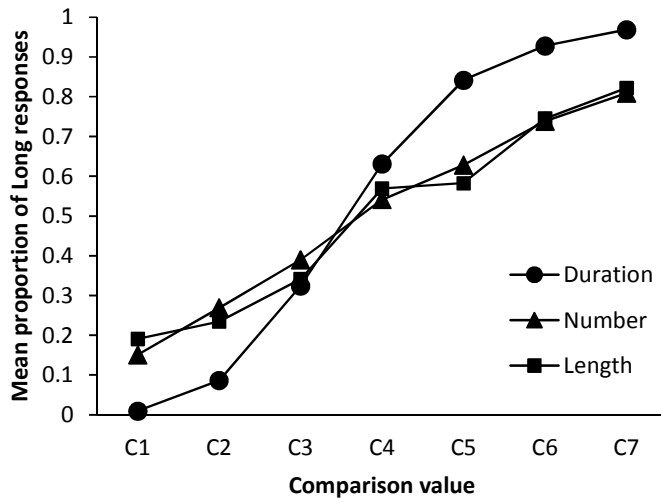


Table 1: Correlations between the measures of STM, executive function and the measures of magnitude perception.

	<i>Duration</i>		<i>Number</i>		<i>Length</i>	
	<i>BP</i>	<i>WR</i>	<i>BP</i>	<i>WR</i>	<i>BP</i>	<i>WR</i>
Spatial Span	.07	.21	-.06	-.20	-.21	-.06
Letter Span	.01	-.44**	.07	-.17	-.11	-.06
Letter Updating	.14	-.16	.12	-.11	-.05	.02
Spatial Updating	.11	-.11	.02	.01	-.16	-.11
Inhibition	.29*	-.39**	.08	-.18	-.21	-.01
Switching	-.08	.09	-.03	-.19	-.15	-.03
Access to Semantic Memory	.16	-.37**	.26*	-.27*	.05	.08

\* $p < .05$ , \*\* $p < .001$

Table 2: Correlations between the measures of STM, executive function and the measures of magnitude perception.

	<i>Duration</i>		<i>Number</i>		<i>Length</i>	
	<i>BP</i>	<i>WR</i>	<i>BP</i>	<i>WR</i>	<i>BP</i>	<i>WR</i>
Spatial Span	.07	-.01	.25	.17	.04	-.09
Letter Span	.03	.04	.08	-.03	.05	.02
Letter Updating	.09	-.01	-.07	.01	-.03	-.32*
Spatial Updating	-.09	-.03	.13	.01	-.30*	-.30*
Inhibition	-.06	-.03	-.02	-.04	-.08	-.20
Switching	.05	.13	-.07	-.02	.07	-.24
Access to Semantic Memory	.04	-.01	-.01	-.27*	.07	.17

\* $p < .05$ , \*\* $p < .001$