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Journal:	*Quarterly Journal of Experimental Psychology*
Manuscript ID	QJE-STD 16-205.R1
Manuscript Type:	Standard Article
Date Submitted by the Author:	03-Oct-2016
Complete List of Authors:	Ogden, Ruth; Liverpool John Moores University, School of Natural Sciences and Psychology Samuels, Michael; Liverpool John Moores University, Natural Sciences and Psycholohy Simmons, Fiona; Liverpool John Moores University, Natural Sciences and Psycholohy Wearden, John; Keele University, Montgomery, Catharine; Liverpool John Moores University, Natural Sciences and Psycholohy
Keywords:	Magnitude, Memory, Executive function, Duration, Number

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

Ruth S Ogden[1], Michael Samuels[1], Fiona Simmons[1], John Wearden[2] and Catharine Montgomery[1]

[1] School of Natural Sciences and Psychology, Liverpool John Moores University, L3 3AF, UK.

[2] School or Psychology, Keele University, ST5 5BG, UK.

Running head: Memory, executive function and magnitude processing.

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; Bueti & 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 Bueti & 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 magnitude differentially require attentional and memory resources. The current paper aimed to explore this. Behavioural evidence suggests that different domains of magnitude may use different attentional and memory resources. When simultaneously processing two magnitude domains (e.g. time and number), the interference is asymmetrical; timing is disrupted by concurrent numerical and spatial processing however numerical (Dormal & Pesanti, 2013; Droit-Volet et al., 2003) and spatial processing (Bottini & Casasanto, 2013; Dormal & Pesanti, 2013) are not disrupted by concurrent timing. This asymmetry may occur because processing duration is more demanding than other magnitudes (Droit-Volet et al., 2003), or less automatic (Dormal & Pesanti, 2013), perhaps requiring greater attention or working memory capacity during processing.

Memory representations of duration also appear to decay differently from those of other magnitude domains. This is illustrated by the phenomenon of subjective shortening, in which the subjective duration of a stimulus is decreased as its period of retention is increased (Wearden, Parry & Stamp, 2002). Subjective shortening occurs with durations in animals (Spetch & Wilkie, 1983) and humans (Wearden & Culpin 1995; Wearden & Ferrara, 1993; Wearden et al., 2002). Attempts to replicate this effect in animals with numerosity (Roberts, Macuda & Brodbeck, 1995), and humans with length (Wearden et al., 2002) have however failed to produce clear evidence for subjective shortening outside of the temporal domain, indicating that it may be a unique quality of temporal information. Similarly, studies exploring the long-term retention of magnitude also suggest differences between temporal, spatial and pitch processing (Ogden, Wearden & Jones, 2008, 2010; Ogden & Jones, 2011). Ogden et al. (2008, 2010) demonstrated that retaining multiple different auditory durations, over a period of delay, led to systematic distortion (shortening or lengthening) of the memory representation of the first encoded duration. Later studies failed to replicate this systematic distortion effect when multiple different pitches or lengths of line were retained over a delay (Ogden & Jones, 2011).

Developmentally, memory for duration also appears to differ from memory for other magnitude domains (McCormack, Brown, Smith & Brock, 2004). Differences in the children's and adults' performance on some temporal tasks have historically been explained by the suggestion that children's memory systems systematically distort representations of duration, making them shorter. This shortening effect disappears by adulthood (Droit-Volet, Clement & Wearden, 2001; McCormack, Brown, Maylor, Derby & Green, 1999). This distortion is not, however, evident when children are processing pitch (i.e. identifying a previously learned pitch from a series of higher and lower pitches). Similarly, distortions in memory representations of duration information present in elderly participants are not replicated when the same participants are judging pitch (McCormack, Brown, Maylor, Richardson & Darby, 2002). Collectively these studies indicate that the way in which duration representations are encoded and/or retained in memory is qualitatively different from the way in which other domains of magnitude are encoded and stored. This may be because the maintenance of duration requires different attentional, working and short-term memory resources than the maintenance of other domains of magnitude.

One way to examine whether the attention and memory demands associated with duration processing differ from those associated with other magnitude processing is to explore the relationships between performance on tasks assessing magnitude processing and tasks assessing general cognitive function (i.e. STM and executive function). Such individual differences approaches have proved fruitful in understanding the wider cognitive demands of timing in adults (Ogden et al., 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 sematic 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 where 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

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

Number-letter Task: Switching

Adapted from Rogers and Monsell (1995) and Miyake et al. (2000), in this task number-letter pairs (e.g. J6) were presented one at a time in one of four quadrants on a computer screen. If the number-letter pair appeared in one of two top quadrants, the participant had to attend to the letter and respond as to whether it was a vowel or a consonant. If it was in the one of the two bottom quadrants, the participant was required to attend to the number and respond to whether it was odd or even. Responses were made via pressing the key "Z" for consonant and odd and the key "/" for vowel and even. The task started with a practice version of three sets. The target was presented in the top half of the screen for 12 trials, then the bottom half for 12 trials and then in a clockwise rotation around all four quadrants for a further 12 trials. The main task then followed the same structure but with 64 trials in each block. The third block of both the practice and main task required participants to switch between making letter and number judgements, meaning that the first two blocks required no switching, were as the third block did. The switch cost was then calculated as the difference between the average reaction times of the third block and the averages of the first two blocks.

Chicago Word Fluency Test: Access to Semantic Memory (adapted from Thurstone & Thurstone, 1938)

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

Results

Figure 1 about here

Figure 1 shows psychophysical functions for duration, number and length. Examination of Figure 1 suggests that responding was orderly, with the proportion of long responses increasing linearly with the magnitude of the comparison. The function for duration discrimination appeared flatter than the number and length functions, suggesting less sensitive performance. A repeated measures ANOVA with within-subject factors of type of magnitude (duration, number, length) and comparison stimulus showed significant main effects of comparison stimulus $F(6, 360) = 965.35$, $p < .001$ $\eta_p^2 = .94$ and magnitude type $F(2, 120) = 12.45$, $p < .001$ $\eta_p^2 = .18$. There was also a significant interaction between magnitude type and comparison stimulus value $F(12, 720) = 7.79$, $p < .001$ $\eta_p^2 = .12$. Bonferroni corrected post-hoc tests showed that responding in the duration discrimination task differed significantly from that in the number and length discrimination tasks ($p < .001$). There was no significant difference between number and length discrimination ($p = .99$).

To explore the relationship between bisection performance and STM and executive function we calculated the bisection point (BP) for duration, number and length for each participant. The BP is the comparison stimulus giving rise to p(long/many) = .50. The bisection points were determined by a method similar to that introduced by Maricq, Roberts, and Church (1981), and used in a number of articles on bisection in humans since (Wearden, 1991; Wearden & Ferrara, 1995). Linear regression was performed on points from the steepest part of the psychophysical function, and this was used to calculate the bisection point, the stimulus value giving rise to 50% long/many responses. Next, the difference limen was calculated, being half the difference between the values giving rise to 75% and 25% long/many responses. The Weber ratio, an index of judgment sensitivity, was then derived by dividing the difference limen by the bisection point. The higher the WR, the flatter the psychophysical function, and the lower the sensitivity to the different values of the stimuli tested. Analysis of the relationship between WRs and difference limen showed a strong positive correlation for duration ($r = .94$, $p < .001$), numerosity ($r = .96$, $p < .001$), and length ($r = .96$, $p < .001$). For brevity, we only report the WR in our analysis. There are a number of different methods of calculating the bisection point from a psychophysical function, but when Wearden and Ferrara (1995) compared some of them results were found to be almost identical.

A repeated measures ANOVA showed significant differences in the bisection points of the three magnitudes $F(2, 118) = 12.73$, $p < .001$ $\eta_p^2 = .17$. Bisection points were significantly greater for duration (M = 9.18, SD = 1.71) than number (M = 8.34, SD = .85) and length (M = 8.27, SD = .77) ($p < .001$). There was no significant difference in BP for number and length ($p = .99$). The same analysis performed on the Weber Ratios also showed a significant effect of magnitude $F(2, 118) = 32.67$, $p < .001$ $\eta_p^2 = .35$. Weber Ratios were significantly greater for duration (M = .16, SD = .09) than number (M = .09, SD = .06) and length (M = .07, SD = .02) ($p < .001$). There was no significant difference in WR for number and length ($p = .37$).

Spearman's correlation coefficient was then used to examine the relationship between STM and executive capacity and magnitude discrimination. Table 1 shows correlation coefficients and p values for the relationships between STM, executive functions and magnitude bisection. Examination of Table 1 suggests that the discrimination of duration, number and length differentially related to executive and STM capacity. Duration discrimination WRs were negatively related to access to sematic memory (CWFT), STM Span (letters) and inhibition (RNG). Better STM, access and inhibitory capacity were therefore all related to improved temporal sensitivity. Duration BP was positive related to inhibition, therefore greater inhibitory capacity was associated with a higher BP. Number discrimination WRs were negatively related to access to semantic memory. Number BP did not relate to executive or STM capacity. There were no relationships between any measure of length discrimination and executive or STM capacity. Taken together these results suggest that duration discrimination is more strongly related to STM and executive capacity than either length or number discrimination.

Discussion

The results of Experiment 1 suggest that the nature of the relationship between STM and executive function task performance and magnitude bisection performance is dependent on the domain of the magnitude being judged. Duration bisection performance was associated with different executive functions to length or number bisection. Duration bisection performance was associated with STM letter span, inhibition and access to semantic memory. Better access, letter span and inhibition were associated with increased sensitivity to time. In addition, poorer inhibition was associated with a reduction in bisection point value. Number bisection was only associated with access to semantic memory, with better access being associated with an increase in bisection point and lower sensitivity to numerosity. Length bisection performance was not associated with any measures of STM or executive function.

These findings suggest that when the ratio between the stimuli being judged is constant across domains (i.e. the S:L ratio is the same for all domains), there is domain specific recruitment of STM and executive functions. Concluding that this indicates that different domains of magnitude have stronger relationships with particular STM and executive resources may however be premature because of the relative differences in task difficulty between the duration, number and length tasks. Although all three tasks had the same S:L ratio (1:2), performance was only equivalent in the length and number tasks. Participants demonstrated relatively less sensitivity to magnitude on the duration task, as evidenced by the flatter psychophysical function and greater WR. This disparity in difficulty may have contributed towards the greater number of associations between duration bisection and STM and executive function than length and number bisection.

Experiment 2 was therefore conducted to establish whether the differences observed in Experiment 1 reflect domain based differences in wider cognitive resource recruitment during magnitude perception or the effect of greater task difficulty. Experiment 2 was a replication of Experiment 1: however, the difficulty of the discrimination judgement was altered. In Experiment 1, performance on the duration discrimination task indicated that the task was more difficult than the number or length discrimination task. To establish whether this disparity contributed to the results, in Experiment 2 the difficulty of the duration discrimination task was relatively reduced by increasing the S:L ratio to 1:3 and the difficulty of the length and number discrimination tasks were relatively *increased* by reducing the S:L/few:manyratio. Wearden et al. (2002) used the same approach in Experiment 3 of their paper to understand the effects of task difficulty on subjective shortening. In addition, we also note that although in Experiment 1, participants were instructed not to count during the bisection tasks, it is possible that they did so anyway, and that this may have affected performance on the numerosity task. In Experiment 2, further safeguards against counting were introduced by 1) increasing the set size in the numerosity task to 24-30 items and 2) reducing the presentation duration from 1,500ms to 500ms.

Experiment 2

Participants

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

Apparatus

As in Experiment 1.

Procedure

The general procedure remained the same as in Experiment 1 with the exception of the stimulus values used in the bisection tasks.

Duration bisection: The durations used changed from Experiment 1 to make the task easier. The short standard was 400ms and the long standard was 1200ms. Comparison values were 400, 533, 667, 800, 933, 1067, 1200ms. All other procedural details remained the same.

Number bisection: The quantities used and the stimulus presentation duration changed from Experiment 1 to make the task harder. The few standard was 24 and the many standard was 30. Comparison values were therefore 24, 25, 26, 27, 28, 29, 30. Stimulus presentation duration was reduced to 500ms. All other procedural details remained the same.

Length bisection: The lengths used and the stimulus presentation duration changed to from Experiment 1 make the task harder. The short standard was 60mm and the long standard was 66mm. Comparison values were therefore 60, 61, 62, 63, 64, 65, 66 mm. Stimulus presentation duration was reduced to 500ms. All other procedural details remained the same.

Results

Figure 2 here

Figure 2 shows psychophysical functions for duration, number and length. Examination of Figure 2 suggests that responding was orderly with the proportion of long responses increasing linearly with the magnitude of the comparison. The function for duration discrimination appeared to be steeper than the number and length functions suggesting more sensitive performance. A repeated measures ANOVA with within-subject factors of type of magnitude (duration, number, length) and comparison stimulus showed significant main effects of comparison stimulus $F(6, 342) = 415.10$, $p <.001$ $\eta_p^2 = .88$ and magnitude $F(2, 114) = 3.24$, $p <.05$ $\eta_p^2 = .06$. There was also a significant interaction between magnitude type and comparison stimulus $F(12, 684) = 19.24$, $p <.001$ $\eta_p^2 = .25$. Bonferroni corrected post-hoc tests showed that responding in the duration discrimination task differed significantly from that in the number and length discrimination tasks ($p < .05$), which themselves did not differ ($p = .18$).

To enable meaningful comparison of the BP and WR for duration, number and length, comparison values were normalised across experiments to 1, 2, 3, 4, 5, 6, and 7. These comparison values were then used in the linear regression to produce BP and WR values using the same method described in Experiment 1. A repeated measures ANOVA showed no significant difference in the bisection points for duration (M = 3.56, SD = .61) than number (M = 4.01, SD = .94) and length (M = 3.86, SD = 1.30). The same analysis performed on the Weber Ratios showed a significant effect of magnitude $F(2, 114) = 4.58$, $p = .01$ $\eta_p^2 = .08$. Weber Ratios were significantly lower for duration (M

= .24, SD = .09) than number (M = .35, SD = .20) and length (M = .39, SD = .36) ($p < .05$). There was no significant difference in WR for number and length ($p = .99$). Sensitivity was therefore significantly greater for duration than for length and number.

Spearman's correlation was then used to examine the relationship between STM and executive capacity and magnitude discrimination. Table 2 shows correlation coefficients and p values for the relationships between magnitude discrimination (BP and WR) and STM and executive function. For this analysis, BP and WR were re-computed using the stimulus values used in the actual experiment. Examination of Table 2 suggests that there were no significant relationships between executive function or STM capacity and duration discrimination (BP, WR). For number discrimination, there was a significant negative relationship between number WR and access. There were no other significant relationships between number discrimination (BP or WR) and STM capacity or executive function. For length discrimination, there were no relationships between STM capacity, access, inhibition or switching. There were however significant negative relationships between measures of updating and length BP and WR.

Table 2 about here

Discussion

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

General Discussion

ATOM suggests that different domains of magnitude (e.g. duration, length and numerosity) are processed in a common magnitude processing system (Bueti & Walsh, 2009; Walsh, 2003). Developmental, behavioural and neurological research offers support for this suggestion. ATOM does not however make specific suggestions about the role of "general cognitive processes" such as STM, WM and executive function in the processing of different magnitude domains (Dormal &

Pesanti, 2012). Consequently, it is unclear whether these general resources are associated with magnitude perception in domain-specific or domain-general ways. This study examined this using an individual differences approach. The findings suggest that the relationship between magnitude bisection performance and STM and executive function performance is complex and varies according to the magnitude domain being judged and the difficulty of the task.

When relatively less difficult, length judgements were not related to STM or executive function. When relatively more difficult, length judgement performance was only associated with updating, with more sensitive length judgments being associated with better updating. Regardless of task difficulty, number bisection performance was only associated with access to semantic memory with better access being associated with greater sensitivity. Critically, the length and number discrimination tasks were equally difficult tasks, yet, the aspects of STM and executive function that were related did not overlap. This is consistent with discrimination in these different domains of magnitude recruiting different aspects of executive functioning, regardless of task difficulty.

When relatively more difficult, duration sensitivity was associated with STM letter span, access to semantic memory and inhibition, with greater sensitivity being associated with better span, access and inhibition. When relatively less difficult however, duration performance was not associated with STM and executive performance. Although the difficulty of duration discrimination was never equivalent to the other domains, the harder duration task was the only discrimination task related to verbal STM and inhibition. This suggests that difficult duration discrimination tasks recruit qualitatively *different* memory and executive resources, rather than relying more heavily on the executive resources recruited by harder versions of the length and number discrimination tasks.

One obvious question is why, if processed by a common processing system, would different magnitudes differentially recruit different STM and executive resources? One suggestion is that although there is evidence for a common processing area in the parietal cortex, there is also evidence that within this, there are specific processing areas, which respond selectively for different magnitude domains (Tudusciuc & Nieder, 2009). In addition, other neural structures, particularly the SMA, maybe uniquely activated during the processing of duration (Coull et al., 2015). These differential outputs may therefore result in differential STM and executive requirements. Alternatively, as suggested by Dormal & Pesanti (2013), the processing of some magnitudes (e.g. number) may be more automatic than others (e.g. duration). Greater automaticity would reduce attentional demands, possibly resulting in differential recruitment of STM and executive resources for more and less automatic magnitude judgments. It is important to note that the extent to which the processing of any magnitude is automatic may in part depend on the modality of presentation. Duration processing, for example, is more sensitive when the stimulus being timed is auditory than visual or vibrotactile (see Jones, Wells & Poliakoff, 2009 for a recent example). In children, more variable performance on visual than auditory timing tasks is thought to be in part due to the greater attentional and working memory demand of visual temporal processing (Zelanti & Droit-Volet, 2012). Therefore, it is possible that, in the current study, duration processing may have been "less automatic" because the stimuli were presented as visual rather than auditory stimuli. Similarly, it is possible that if number was presented as auditory stimuli (e.g. a series of tones) processing would become less automatic than when number is presented visually. Furthermore, these differences in modality may influence how task performance relates to wider cognitive resources. Further research should clarify the effect of modality on the role of wider cognition in magnitude processing.

Fundamental properties of the magnitude itself may also drive differential STM and executive function requirements. Droit-Volet et al. (2008) articulate this point by distinguishing between sequential and non-sequential magnitude properties. Duration is sequential, in that there is a continuous flow of events which requires accumulation across time. Length and number, when presented as in the current experiments, are non-sequential, in that all stimuli are presented as a single discrete object. Droit-Volet et al. (2008) suggest that the sequential nature of duration may necessitate its processing to require different cognitive resources than other, static non-sequential, domains of magnitude. Particularly, they suggest that duration processing may be particularly demanding of attentional and working memory resources because the perceiver must maintain their attention on the stimulus over a longer period of time. This is supported by Coull et al.'s (2015) fMRI comparison of activation during sequential and non-sequential length and duration processing. Coull et al. (2015) suggest that the differential activation observed in the SMA, bilateral inferior frontal gyrus, left anterior insular, basal ganglia and bilateral middle/superior temporal cortex, during sequential and non-sequential processing perhaps reflects activity associated with WM and sequential processing in during duration processing, which is absent or reduced during other forms of static magnitude processing. In the current study, it is interesting to consider that verbal STM was *only* related to the processing of durations. It has been proposed that the auditory-verbal short-term store plays a crucial role in the retention of sequential information (see Baddeley, 2012 for a discussion). Consequently, the unique relationship between verbal STM and duration may reflect the intrinsically sequential nature of duration compared to the static nature of area and number.

The idea that sequentiality may be critical in establishing the similarities and differences between the processing and remembering of different magnitude domains is supported because certain phenomena associated with duration processing are only replicated in number and length processing when number and length are presented sequentially (i.e. the number of dots on a screen increases over time or the length of a line increases over time). For example, development aldifferences in duration and length/number processing are present when number and length are presented non-sequentially, but absent when duration, number and length are presented sequentially (Droit-Volet et al., 2008). The phenomenon in which estimates of duration are lengthened when preceded by trains of clicks has also been found for length and number judgements, but only when the stimuli are presented sequentially; clicks had no effect when length and number were presented non-sequentially (Droit-Volet, 2010). Similarly, fear induced emotional arousal only affects length and number judgments in comparable ways to duration when the length and number stimuli are presented sequentially (Droit-Volet, 2013). Indeed, duration processing can be unaffected by the simultaneous processing of number or length if number and length are presented sequentially rather than non-sequentially (Lambrechts, Walsh, & Van Wassenhove, 2013). One explanation for these disparities is that comparable effects only manifest when the STM and attentional demands of the different magnitude domains are comparable, and that this only occurs when number and length are presented sequentially.

Sequentially presented magnitudes may require different memory and executive resources during the initial period of perception because an attentional focus must be maintained throughout the stimulus presentation. These increased attentional demands may also carry over into their encoding and maintenance in memory. One possibility is that sequential stimuli require some form of “replaying” during encoding and recall, which would be demanding of cognitive resources, whereas static, non-sequential stimuli are simply encoded, recalled and maintained as static mental images, which may be relatively less demanding of cognitive resources. The vulnerability of duration memories to distortion or decay (Droit-Volet et al., 2001; Ogden et al., 2008, 2010, Ogden & Jones, 2011; McCormack et al 1999, McCormack et al., 2002; Wearden et al., 2002) is supportive of these suggestions. However, although sequential processing may necessitate different STM and executive resources to non-sequential processing, it is unlikely to be the sole driver of the differences observed in this study. This is reflected in the absence of overlap in the STM and executive resources recruited during the non-sequentially presented length and number tasks despite them having equivalent difficulty.

A further factor which may influence STM and executive function recruitment during magnitude perception is the extent to which magnitude bisection performance is influenced by the use of long-term memory (LTM) representations of quantity. In the current studies, both number and duration bisection performance were related to access to semantic memory. For number bisection, this perhaps reflects the accessing of abstract numerical representations stored in LTM. For example, participants may have used their approximate number system (ANS Halberda & Feigenson, 2008), which is an imprecise, non-counting based, system for representing quantity, to aid bisection performance. A similar strategy may also have been used in the duration bisection tasks as it has previously been suggested that LTM representations of “key durations” e.g. 1 second may influence performance on temporal tasks (Ogden et al., 2014; Wearden, Jones, & Todd, 2006). To understand the extent to which long-term memory representations of magnitude are used in bisection tasks, further research should compare how wider cognitive resources relate to magnitude perception when counting is prevented (e.g. through sub-vocalisation) and reliance on the ANS/LTM is high with when counting is explicitly instructed and reliance on the ANS/LTM is relatively lower.

It should be noted that, although the present study highlights differential relationships between wider cognitive performance and duration, number and length perception, the correlations between performance on any of the tasks are only weak-moderate and *p* values were not corrected for multiple comparisons. It would therefore seem that whilst individual differences in magnitude perception are associated, in part, with individual differences in STM and executive function, other factors (e.g. decision thresholds, motivation, acuity of underlying magnitude representation) are also affecting performance.

A complicating factor in the present study was the effect of task difficulty. Correlations between STM and executive performance measures and duration perception indices depended on whether the duration task was easy (Experiment 2) or harder (Experiment 1). This does not mean that the resources recruited are different in the easy and more difficult case, only that the easy task is not sensitive to individual differences in STM and executive performance. For example, if a person is given one item to remember, then differences in the ability to this between individuals may be negligible and unrelated to other measures of memory. In contrast, if people are given 12 or 15 items to remember, performance may be strongly related to more general memory capacity. However, in both cases memory is used: the basic underlying psychological process involved does not differ. The effect of task difficulty raises a number of methodological and theoretical problems. For one thing, there is the question of how task difficulty across different magnitude types should be equated. In the case of bisection, should it be a measure of correct responses, the sensitivity of judgements (assessed by WR) or both? More problematical still are potential effects of task difficulty when different groups are compared, such as children of different ages, with or without an adult comparison group. Sensitivity to duration on bisection tasks increases with age in children (Droit-Volet & Wearden, 2001; McCormack et al., 1999), so different patterns of correlations at different ages between measures of cognitive performance and timing behaviour (as in Droit-Volet & Zelanti 2013; Zelanti & Droit-Volet, 2001, 2012) may be in part due to changes in task difficulty. Further research should therefore focus on understanding precisely how task difficulty mediates the relationship between cognitive function and magnitude discrimination.

In conclusion, it is clear that there are some domain based differences in the recruitment of STM and executive function resources during magnitude bisection. Whilst this does not preclude the idea of a universal magnitude processing system, it suggests that this system may differentially recruit wider cognitive resources when processing different magnitude domains, either during the actual perceptual process, or downstream during memory encoding and the production of behavioural output. Duration perception appears to be more demanding of wider cognitive 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.

Table list

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

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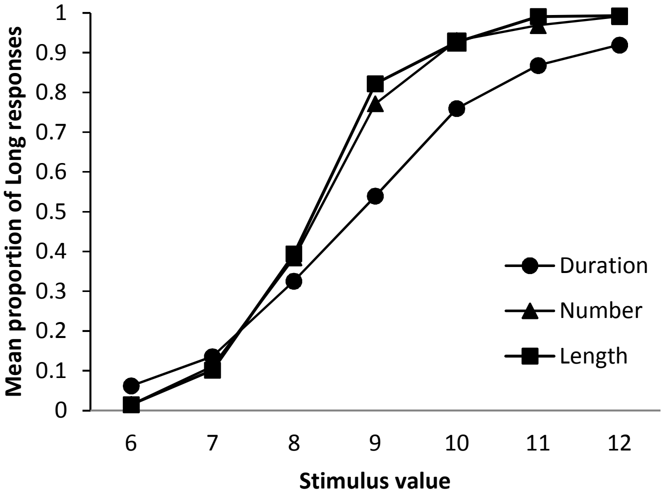

Figure 2: Psychophysical functions from Experiment 2. Mean proportion of LONG/MANY responses plotted against the comparison value. Data are shown separately for the duration, number and length conditions.

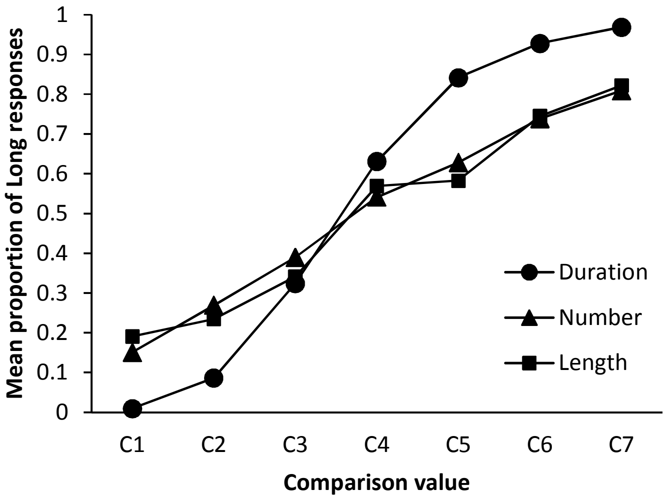

Table 1: Correlations between the measures of STM, executive function and the measures of magnitude perception.

	Duration		*Number*		*Length*	
	BP	*WR*	*BP*	*WR*	*BP*	*WR*
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.

	Duration		*Number*		*Length*	
	BP	*WR*	*BP*	*WR*	*BP*	*WR*
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