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Mathematics Students Demonstrate Superior Visuo-Spatial Working Memory to Humanities Students Under Conditions of Low Central Executive Processing Load

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Abstract

Previous research has demonstrated that working memory performance is linked to mathematics achievement. Most previous studies have involved children and arithmetic rather than more advanced forms of mathematics. This study compared the performance of groups of adult mathematics and humanities students. Experiment 1 employed verbal and visuo-spatial working memory span tasks using a novel face-matching processing element. Results showed that mathematics students had greater working memory capacity in the visuo-spatial domain only. Experiment 2 replicated this and demonstrated that neither visuo-spatial short-term memory nor endogenous spatial attention explained the visuo-spatial working memory differences. Experiment 3 used working memory span tasks with more traditional verbal or visuo-spatial processing elements to explore the effect of processing type. In this study mathematics students showed superior visuo-spatial working memory capacity only when the processing involved had a comparatively low level of central executive involvement. Both visuo-spatial working memory capacity and general visuo-spatial skills predicted mathematics achievement.

Keywords: visuo-spatial working memory, adult mathematics, mathematical cognition, visuo-spatial short-term memory, endogenous attention

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Mathematics is useful for many aspects of everyday living. Its use ranges from basic arithmetic, such as calculating change in a shop, through to advanced mathematics involved in, for example, physics and engineering. Success in mathematics also has wider reaching consequences in terms of improved reasoning and problem solving skills (Attridge & Inglis, 2013; Nisbett, Fong, Lehman, & Cheng, 1987; Smith, 2004) as well as enhanced employability and earning potential (Bynner, 1997; Rivera-Batiz, 1992). Individual differences in mathematics are underpinned by a range of different domain-specific and domain-general factors, as specified in multi-component models of mathematical cognition (Fuchs et al., 2010; Geary, 2004, 2011; LeFevre et al., 2010).

A key domain-general skill linked to individual differences in mathematics is working memory, the ability to temporarily store and manipulate information in mind (Baddeley, 1992). Individuals who perform well in tests of mathematics have been consistently found to also possess good working memory skills (e.g. Gathercole, Pickering, Knight, & Stegmann, 2004; Holmes & Adams, 2006; Imbo & LeFevre, 2010; Leikin, Paz-Baruch, & Leikin, 2013; Raghubar, Barnes, & Hecht, 2010; Wilson & Swanson, 2001). The vast majority of this research has focused on arithmetic, most often with children, and there has been comparatively little focusing on the cognitive skills associated with the performance of advanced mathematics in adults (Wei, Yuan, Chen, & Zhou, 2012).

Relationships between working memory and mathematics may differ for adults and children however. Firstly, working memory has been found to play a larger role in the procedural strategies favored by children, as compared to the greater use of retrieval strategies and more efficient use of procedural strategies in adults (Imbo & Vandierendonck, 2008). Secondly, research involving children might also reflect the role of working memory in learning mathematics rather than the proficient performance of mathematics, and finally, working memory may play a larger role in the arithmetic that dominates early mathematics, rather than the wider range of areas encountered later in study.

A further question concerns the type of working memory that best predicts mathematics outcomes. The model of working memory typically adopted in this field comprises verbal (phonological loop) and visuo-spatial (visuo-spatial sketchpad) storage components and an executive component (central executive) that coordinates them (Baddeley, 2003). While the central executive is considered a domain-general resource, most executive working memory tasks involve the storage of information in either the verbal or visuospatial domain. There is mixed evidence concerning whether mathematics performance is more strongly related to verbal or visuo-spatial storage. Some studies, particularly those carried out with children, suggest verbal working memory shows a stronger link with mathematics (Bayliss, Jarrold, Gunn, & Baddeley, 2003; Friso-van den Bos, van der Ven, Kroesbergen, & van Luit, 2013; Östergren & Träff, 2013). Moreover, there is some evidence that the role of verbal working memory may increase between the ages of 7 and 12 years, while the role of visuospatial working memory may decrease (Van de Weijer-Bergsma, Kroesbergen, & Van Luit, 2015; but see Geary, Nicholas, Li, & Sun, 2017).

In contrast, other studies find a stronger relationship between visuo-spatial working memory capacity and mathematics (e.g. David, 2012; Leikin et al., 2013) and suggest that the role of visuospatial working memory may increase with age between 6 and 15 years (Li & Geary, 2013, 2017). Szűcs, Devine, Soltesz, Nobes, and Gabriel (2014) examined a wide range of cognitive abilities linked to mathematics in 100 seven to ten year old children and found that whilst visuo-spatial working memory predicted arithmetic performance, verbal working memory did not. To our knowledge, only two studies to date have directly compared the contribution of verbal and visuospatial working memory in arithmetic in adults, one finding a greater role for verbal as compared to visuospatial working memory (Logie, Gilhooly, & Wynn, 1994), and the other a greater role for visuospatial as compared to verbal working memory (Clearman, Klinger, & Szűcs, 2017). However, no studies have directly compared the role of verbal and visuospatial working memory in more general advanced mathematics in adulthood.

One established method of studying the relationship between advanced mathematics and other cognitive skills in adults is to compare students who study mathematics with those who do not (e.g. Attridge & Inglis, 2013; Inglis & Simpson, 2009). While this cannot tell us about causality, it can indicate the presence or absence of relationships. Dark and Benbow used a similar approach to compare the role of working memory in mathematically and verbally gifted adolescents (12-14-years-old) across a series of studies (Dark & Benbow, 1990, 1991).

They found that mathematically gifted adolescents had greater capacity for the simple storage of digits and spatial information in memory than verbally gifted adolescents as well as greater ability to update paired associations between letters and digits in working memory. Greater ability to update paired associations between letters and spatial locations was found in one study (Dark & Benbow, 1990) but not another (Dark & Benbow, 1991). Taken together, these findings suggest that general advanced mathematics may be associated with enhanced short-term and working memory, however it remains to be seen whether this relationship is present in adults.

In this paper we present three experiments which investigate differences in both verbal and visuospatial working memory capacity between adult mathematics and humanities students[i]. Examining the working memory performance of skilled adult mathematicians will help inform models of which working memory resources are associated with the proficient solving of mathematical problems, and how these associations are influenced by age, skill level and type of mathematical knowledge. It is yet to be shown whether adults who are proficient at mathematics have superior working memory capacity to those who are less skilled at mathematics, and if so, whether this depends on the type of material to be stored. If working memory plays a critical role in mathematics, as suggested by literature investigating both verbal and visuo-spatial working memory (e.g. Dark & Benbow, 1990, 1991, 1994; Szűcs et al., 2014), we would expect to see greater working memory capacity in skilled mathematicians compared to an equivalent group who are not skilled in mathematics in both verbal and visuospatial domains.

Experiment 1

Experiment 1 investigated differences between the working memory storage capacity for number, word and visuo-spatial stimuli of adult mathematics and humanities students. Individuals with good visuo-spatial working memory have been shown to have higher levels of mathematics achievement (David, 2012; Leikin et al., 2013; Li & Geary, 2013; Szűcs et al., 2014). Previous research with adults (Fürst & Hitch, 2000; Imbo & Vandierendonck, 2007; Logie et al., 1994) and children (Adams & Hitch, 1997; Gathercole et al., 2004; Jarvis & Gathercole, 2003; Passolunghi, Vercelloni, & Schadee, 2007; Purpura & Ganley, 2014) has also suggested verbal working memory capacity is linked to mathematics achievement. Therefore, we predicted that mathematics undergraduates would have greater working memory capacity for both verbal and visuo-spatial information than humanities undergraduates.

Traditionally, span tasks used to measure working memory capacity have included a processing element, such as reading, performing arithmetic or judging the symmetry of pairs of objects, interweaved with to-be-remembered storage items, such as numbers, words or the orientation of arrows (Friedman & Miyake, 2004; Unsworth & Engle, 2007). At the end of each set, the to-be-remembered items have to be recalled, in correct serial order. However, the format of verbal and visuo-spatial processing elements, and whether they are combined with storage items from the same or different domain, impacts the number of items remembered. It can also affect the strength of correlations between working memory and higher-level cognitive tasks (Jarrold, Tam, Baddeley, & Harvey, 2011; Shah & Miyake, 1996; Vergauwe, Barrouillet, & Camos, 2010). Therefore, choice of the type and format of the processing element in a working memory span task is extremely important. To reduce the impact of the processing element on the storage capacity for different types of material, we used the same novel face-matching task (Burton, White, & McNeill, 2010) for the processing element in all conditions. This was a basic visual comparison involving no spatial transformation (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001) or verbal processing and was therefore chosen because it was as neutral as possible with regard to the storage stimuli used.

Method

Participants

55 participants were recruited from undergraduates at the University of Nottingham: 27 (10 male) to a mathematics students group and 28 (8 male) to a humanities students group. All participants gave written informed consent and received an inconvenience allowance of £6. The study was conducted in accordance with the British Psychological Society's (BPS) Code of Human Research Ethics. The mathematics students group comprised 19 students studying for a Mathematics degree and 8 students studying for an Economics degree[ii]. Their ages ranged from 18.33 to 30.58 years (*M* = 20.43; *SD* = 2.29). Economics students were included because degree modules for this subject contain substantial mathematics elements and all economics undergraduates had studied mathematics at A level (advanced standard examinations completed by UK students at 18 years of age). The humanities students group comprised English, History and Sociology undergraduates, who were not studying mathematics modules at University. Their ages ranged from 18.67 to 28.92 years (*M* = 20.72; *SD* = 2.35). Five of the humanities students group were later discovered to have studied mathematics at A level and their data was therefore discarded. The remaining participants in this group had not studied mathematics for a mean of 4.29 years (*SD* = 2.71). All experiments received ethical approval from the ethics committee of the School of Psychology, University of Nottingham.

Equipment and Materials

A Viglen Pentium D computer, running Windows XP and PsychoPy2 version 1.73.06 (Peirce, 2007), was used to present stimuli and record latencies and accuracy. Participants' responses were collected via keyboard, numeric keypad or USB mouse depending on the task.

Working Memory Tasks

There were three working memory span tasks which had the same processing element interweaved with different storage elements.

For the processing element, participants were presented with two photographs of faces (8.5 cm x 9.5 cm high) side by side on screen and had to make a judgement as to whether they were different pictures of the same person or not, responding with the 'y' or 'n' key on the keyboard. The pictures were all taken from the Glasgow Unfamiliar Face Database, which shows a high internal reliability when used in a face-matching task (Burton et al., 2010). Faces presented were all white, Western, with neutral expressions and matching pairs were presented in approximately 50% of the trials.

The storage element of each span task consisted of numerical, word or visuo-spatial items presented in the center of the screen (size 2cm). Items were taken from a group of nine possible stimuli in each condition. Numerical items included the digits 1 to 9. Word items were animal words (fly, cow, dog, bat, ape, fox, elk, hen, ram). Visuo-spatial items employed a black 3 x 3 grid (each square 6cm wide x 6cm high) with a red dot (diameter 3 cm) placed in one of the nine possible locations on the grid.

Each trial comprised an interweaved series of processing elements and storage items (see Figure 1). Each pair of faces (processing element) was presented on screen for 3 seconds, although participants were still able to respond after this time. Storage items were presented for 500 ms, commencing 500 ms after a response had been given to the preceding pair of faces. The next pair of faces was presented 500ms after the storage item disappeared from screen. Once all storage items had been presented, a “ ? ” appeared in the center of the screen that prompted the participants to recall the storage items, in their order of presentation. In the number condition, participants said the numbers aloud and the experimenter keyed the response into the USB numeric keypad. In the word condition, participants said the words out loud, the experimenter coded them and then entered them via the USB numeric keypad. In the visuo-spatial condition, a black 3 x 3 grid appeared on screen immediately after the “ ? ” and participants recalled the serial order of the red dot by clicking on the grid, using the USB mouse. Once recall was completed, the participant pressed the space bar to begin the next trial. Each of span lengths 2 to 7 was presented three times, giving 18 span sets (trials) in each of the three conditions. Each of the nine possible items within each set was presented approximately equally.

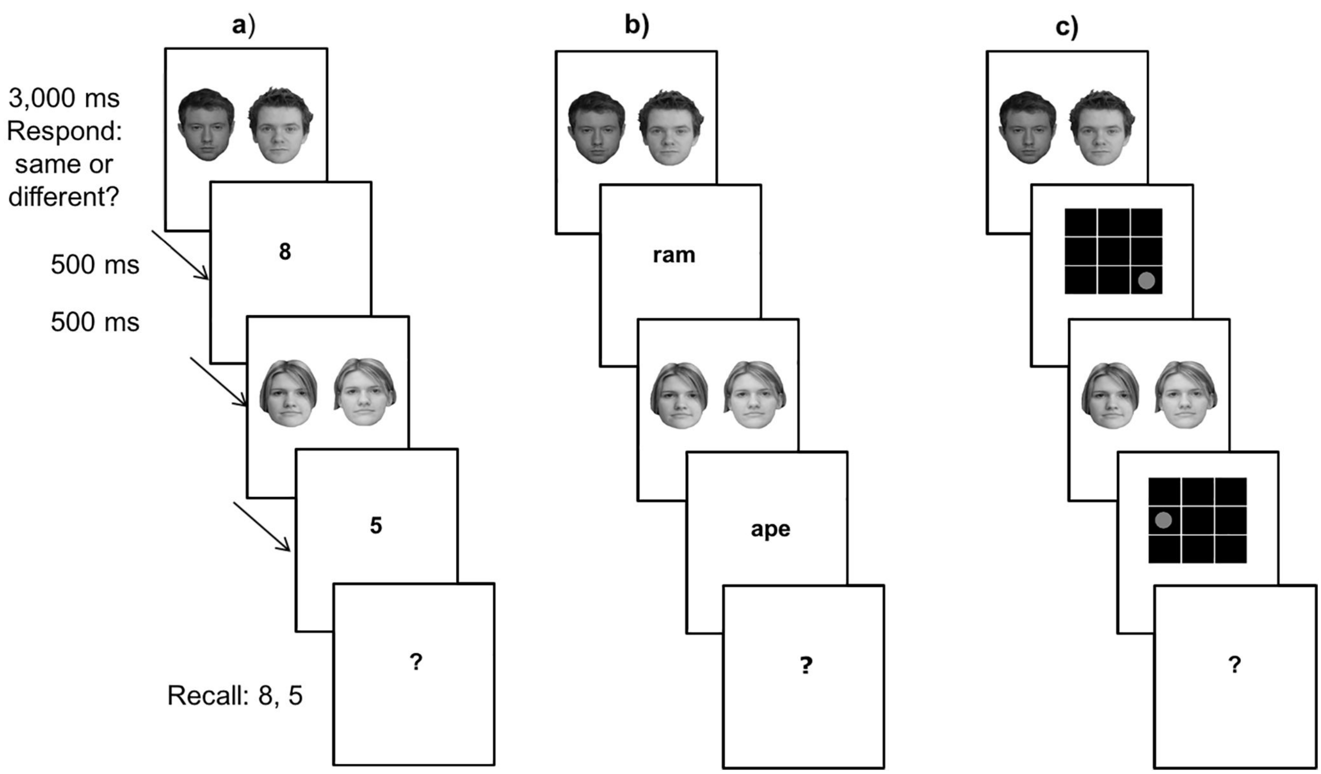

Figure 1. Experiment 1. Examples of trial sequences (2 Span) in the a) numerical, b) word and c) visuo-spatial conditions.

Additional Materials

The Matrix Reasoning and Vocabulary subtests from the Wechsler Abbreviated Scale of Intelligence (WASI; Psychological Corporation, 1999) were administered, using the standard procedures and scores, to enable comparison of the IQ of the two groups. The Woodcock-Johnson Calculation Test (Woodcock, McGrew, & Mather, 2001) was also administered. Questions ranged from arithmetic, fractions and long division through to items such as matrices, integration and trigonometry.

Procedure

All participants were tested individually by the same experimenter and each session lasted around one hour. After initial instructions, participants practiced 6 trials of the face-matching task. All three span tasks commenced with a practice of one 2-span set and one 3-span set comprising both processing and storage tasks, before the 18 experimental sets were administered. The order in which the three span tasks were presented was counterbalanced across participants and the order of presentation of span sets and the presentation of items within each set was randomized. Participants then completed the Matrix Reasoning and Vocabulary tests, the order of which was counterbalanced across participants. Finally, participants completed the Calculation Test.

Results

Seven participants (3 mathematics group; 4 humanities group) were excluded from the current analyses for having an unacceptably high (>15%) error rate in the processing task. One influential outlier was detected in the humanities students group in the visuo-spatial condition, with a Cook's Distance score > 1, and this male participant's data was discarded for analysis purposes.

This left data for 24 (10 male) participants in the mathematics students group and 18 (7 male) in the humanities students group. For all three experiments in this paper, controlling for age and gender had no significant impact on analyses, so age and gender were not included in any analyses reported. Also, for all three experiments, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity where necessary and Bonferroni corrections for multiple comparisons were used. For all analyses other than ANCOVA or correlations involving non-normal distributions, *Pearson's correlations coefficient*, *r,* is used as a measure of effect size. We have employed this measure rather than other measures of effect sizes, such as *Cohen's d*, as it is easily interpreted and compared because its value ranges from 0 to 1. Values for r are widely interpreted as follows: $r = .10$ (small effect); $r = .30$ (medium effect); $r = .50$ (large effect) (Field, 2009, p. 57)

Standardized Tests

An independent t-test to compare the two groups' Calculation Test scores confirmed that the mathematics students group ($M = 36.83$, $SD = 2.91$) were significantly better at mathematics than the humanities students group ($M = 24.61$, $SD = 3.57$), $t(40) = 12.22$, $p < .001$, $r = .89$. Independent t-tests also showed that there was no significant difference between the two groups for Matrix Reasoning (mathematics students: $M = 29.42$, $SD = 2.47$; humanities students: $M = 28.72$, $SD = 2.78$), $t(40) = 0.86$, $p = .398$, $r = .13$ or for Vocabulary, (mathematics students: $M = 61.83$, $SD = 6.27$; humanities students: $M = 65.17$, $SD = 5.73$), $t(40) = -1.77$, $p = .085$, $r = .27$.

Storage Element

Proportion correct scores were first calculated for each participant for the number of storage items recalled in their correct serial position (Conway et al., 2005). Descriptive statistics by group are shown in Figure 2a. A 2(group: mathematics, humanities) x 3(working memory storage type: number, visuo-spatial, word) mixed Analysis of Variance (ANOVA) was then performed on these scores. There was no main effect of group, $F(1,40) = 3.57$, $p = .066$, $r = .29$. There was a significant main effect of storage type, $F(1.57,62.93) = 51.01$, $p < .001$, $r = .67$. Pairwise comparisons showed participants were significantly more accurate in the number condition than the visuo-spatial condition, $p < .001$, or the word condition, $p < .001$. Participants were also more accurate in the visuo-spatial condition than the word condition, $p = .003$.

There was a significant group x working memory storage type interaction, $F(1.57,62.93) = 6.01$, $p = .007$, $r = .30$. Tests of Bonferroni-corrected simple main effects showed that the mathematics students group had significantly greater scores than the humanities students group in the visuo-spatial condition, $F(1,40) = 19.10$, $p < .001$, $r = .57$, but there was no significant difference in performance between the two groups in the verbal domain, either for word span $F(1,40) = 0.01$, $p = .921$, $r = .02$ or number span $F(1,40) = 0.08$, $p = .783$, $r = .04$. Word span and number span scores were significantly correlated, $r = .59$, $p < .001$, but neither were significantly correlated with visuo-spatial span scores: word span $r_s = .16$, $p = .312$; number span $r_s = .12$, $p = .434$.

There was a significant correlation between Woodcock-Johnson Calculation scores and visuo-spatial span performance, $r_s = .56$, $p < .001$, but neither storage types in the verbal domain correlated with mathematics scores: word span $r_s = .18$, $p = .264$; number span $r_s = .07$, $p = .681$.

To further explore the presence or lack of group differences for spatial, word and number storage span scores we conducted a series of Welch's *t*-tests (allowing for unequal variance due to unequal group sizes) to test for differences between and equivalence of group mean scores (Lakens, 2017). To test for group equivalence, we used the two one-sided test (TOST) procedure and set equivalence bounds of raw score differences of -.05 and .05 (i.e. groups means were treated as equivalent if mathematicians' scores were less than 5% above or below non-mathematicians' scores). For visuo-spatial span scores, Welch's *t*-test for group difference was significant, $t(38.42) = 4.40$, $p < .001$, and Welch's equivalence *t*-test was non-significant, $t(38.42) = 1.39$, $p = .913$. For word span scores, Welch's *t*-test for group difference was non-significant, $t(38.06) = 0.08$, $p = .940$, and Welch's equivalence *t*-test was significant, $t(38.06) = -1.82$, $p = .038$. For number span scores, Welch's *t*-test for group difference was non-significant, $t(35.71) = 0.25$, $p = .807$ and Welch's equivalence *t*-test was significant, $t(35.71) = -3.85$, $p < .001$. In other words, there is evidence that the groups differed in their visuo-spatial span scores and there is evidence that the groups were equivalent in their word span and number span scores.

Bayesian analysis was also conducted to examine the presence or lack of group differences for number, word and visuo-spatial storage span scores. The analysis was conducted using default prior in JASP to conduct simple Bayesian *t*-tests for group differences in correct scores for the different conditions. There was moderate evidence for the null hypothesis that the mathematics and humanities groups were the same in the number ($BF_{10} = 0.323$) and word ($BF_{10} = 0.303$) conditions. There was, however, very strong evidence for the alternative hypothesis, that the mathematics and humanities groups were different in the visuo-spatial condition ($BF_{10} = 46.724$).

Processing Element

Mean accuracy and median RT on the face-matching task were calculated for each participant in each of the three working memory span conditions and analyzed with separate 2(group: mathematics, humanities) x 3(working memory storage type: number, visuo-spatial, word) mixed ANOVAs (see Table 1 for descriptive statistics).

Table 1

Mean (M) and Standard Error (SE) Accuracy and Reaction Time in the Face-Matching Task by Group and Storage Type Condition for Experiments 1 and 2

	Experiment 1				Experiment 2			
	Accuracy (Pc)		Reaction Time (ms)		Accuracy (Pc)		Reaction Time (ms)	
Group	***M***	***SE***	***M***	***SE***	***M***	***SE***	***M***	***SE***
Storage Condition: Number								
Mathematics	.94	.01	1264	63	.95	.01	1304	56
Humanities	.95	.01	1326	72	.94	.01	1252	59
Storage Condition: Visuo-spatial								
Mathematics	.94	.01	1287	50	.95	.01	1311	50
Humanities	.96	.01	1421	86	.95	.01	1129	48
Storage Condition: Word								
Mathematics	.93	.01	1323	63				
Humanities	.93	.01	1403	76				

Note. Pc = Proportion correct.

For accuracy, there was no main effect of group, $F(1,40) = 2.47$, $p = .124$, $r = .24$ or group x span type interaction, $F(2,80) = 0.34$, $p = .716$, $r = .09$. There was a significant main effect of storage type, $F(2,80) = 5.57$, $p = .005$, $r = .42$. Pairwise comparisons showed no significant difference in face-matching accuracy for the number and visuo-spatial storage conditions, $p = 1.00$, but greater face-matching accuracy for both the number ($p = .034$) and visuo-spatial ($p = .016$) storage conditions than the word storage condition.

Face-matching latencies showed no main effect of group, $F(1,40) = 1.03$, $p = .316$, $r = .16$ or group x storage type interaction, $F(2,80) = 0.90$, $p = .411$, $r = .15$. There was a significant main effect of storage type. $F(2,80) = 3.52$, $p = .034$, $r = .21$. Pairwise comparisons revealed face-matching latencies in the number condition were faster than in the word condition, $p = .035$. There was no significant difference in face-matching latencies between the visuo-spatial and word conditions $p = 1.00$, or between number and visuo-spatial conditions, $p = .099$.

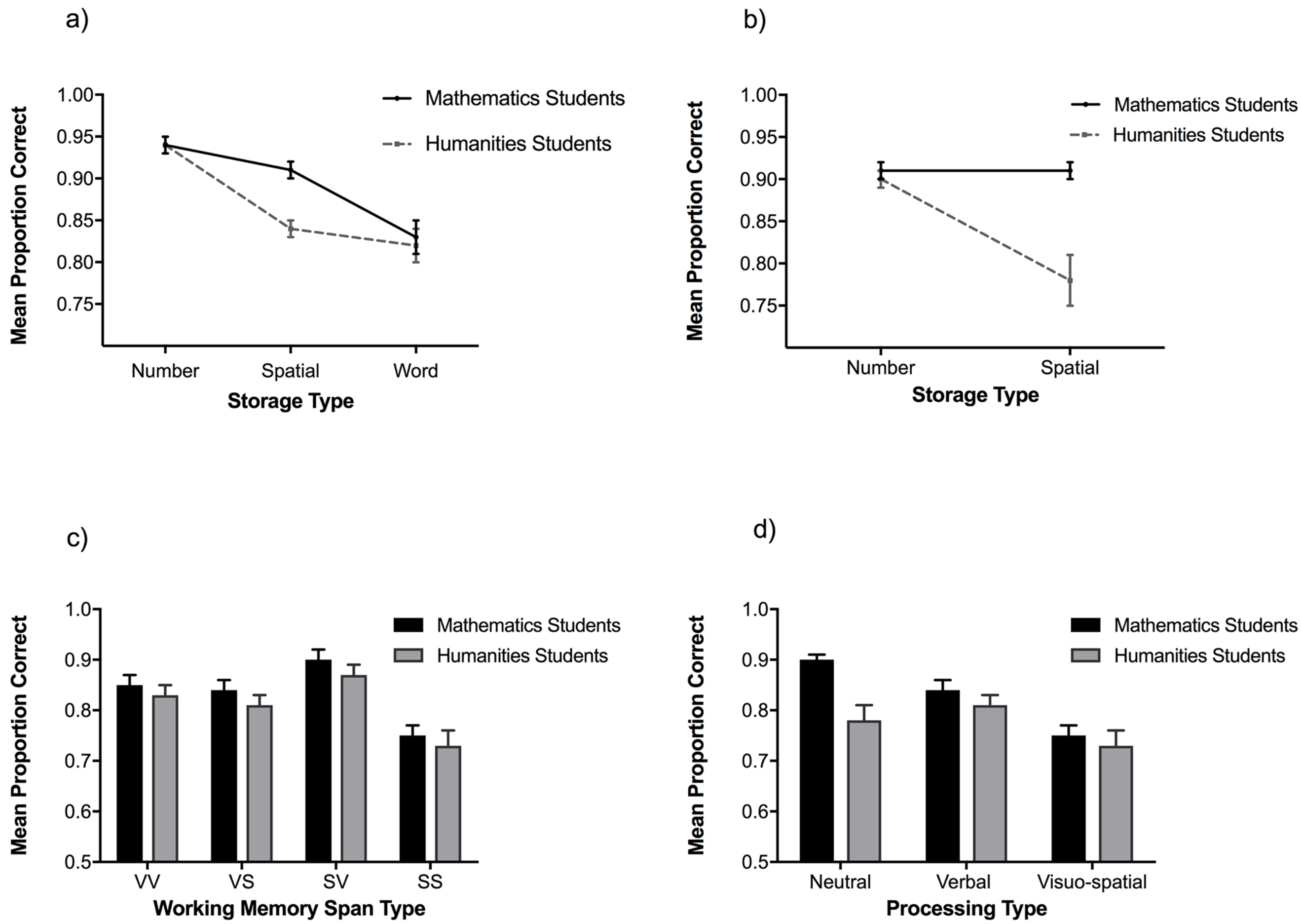

Figure 2. Storage accuracy for each working memory span type for each participant group in a) Experiment 1, b) Experiment 2, c) Experiment 3, d) the comparison between the visuo-spatial storage conditions in Experiments 2 and 3.

Note. VV = verbal processing, verbal storage; VS = verbal processing, visuo-spatial storage; SV = visuo-spatial processing, verbal storage; SS = visuo-spatial processing, visuo-spatial storage. Error bars represent the standard error.

Discussion

We found that mathematics students have superior working memory capacity within the visuo-spatial, but not the verbal domain. There was a large difference between groups for the visuo-spatial storage condition, where mathematics students were around 10% more accurate than the humanities students. This was underlined by the strong correlation between visuo-spatial span and Woodcock-Johnson Calculation scores, which revealed visuo-spatial working memory capacity has a significant association with mathematics achievement. Contrary to predictions, there were no differences between the groups of mathematics and humanities students in either the word or numerical conditions. The predictions were based on results of previous studies that involved young children (Adams & Hitch, 1997; Gathercole et al., 2004; Passolunghi et al., 2007; Purpura & Ganley, 2014) and adolescents (Dark & Benbow, 1990, 1991, 1994; Jarvis & Gathercole, 2003) and therefore may reflect a role for verbal working memory resources in learning rather than doing mathematics. Dual task studies with adults (Fürst & Hitch, 2000; Imbo & Vandierendonck, 2007; Logie et al., 1994) have shown that verbal working memory resources are involved in mathematics, but this does not necessarily mean that mathematicians are better at using these resources. Overall, these findings suggest that visuo-spatial working memory may be linked to advanced mathematics in adults.

There were no group differences on the processing element of the task. In both groups, there was a medium-sized effect of storage condition on the face-matching task where accuracy was slightly worse in the word condition than in the number and visuo-spatial conditions. This is consistent with previous findings that performance on the processing element of a working memory span task usually positively correlates with performance on the storage element (Conway et al., 2005) and performance for word storage was worse than for numbers and visuo-spatial storage, as shown in Figure 2a. Similarly, a small effect of storage condition indicated that processing latencies were faster in the number condition than in the word and visuo-spatial conditions, reflecting the greater performance for number storage items. Descriptive statistics in Table 1 show longer processing times for the humanities students compared to the mathematics students in each of the three conditions in Experiment 1, suggesting processing latencies may have been affected by the cognitive load of the storage tasks. However, none of the between-group differences for processing latencies were significant.

In Experiment 2 we investigated potential mechanisms to account for our finding that mathematics students had a greater working memory capacity for visuo-spatial information than humanities students. We explored whether differences in visuo-spatial short-term memory (with no processing) or controlled spatial attention could account for this effect. Research has found that the short-term storage of information is required when solving mathematical problems (Adams & Hitch, 1997; Trbovich & LeFevre, 2003) and that the visuo-spatial sketchpad may be used during calculation (Lee & Kang, 2002; Logie et al., 1994; Trbovich & LeFevre, 2003). Visuo-spatial short-term memory performance, with no processing element present, has been linked to mathematics in adults (Wei et al., 2012). It may therefore be that mathematics students simply have a superior ability to store information within the visuo-spatial sketchpad.

An alternative explanation for mathematics students' superior visuo-spatial working memory capacity could be better endogenous spatial attention. Endogenous attention is believed to be important for refreshing items in memory and for ensuring items remain available for further processing and/or recall (e.g. Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Cowan, 2001; Engle, 2002). Previous experimental research suggests an overlap between endogenous attention and visuo-spatial working memory (Astle & Scerif, 2011; Awh, Jonides, & Reuter-Lorenz, 1998; Awh, Vogel, & Oh, 2006; Chun & Turk-Browne, 2007; Gazzaley & Nobre, 2012).

Experiment 2 again compared the working memory storage capacity of undergraduate mathematicians and undergraduate humanities students for verbal and visuo-spatial information. Only the number condition was used in the verbal domain as, in Experiment 1, the number and word conditions showed similar patterns of association with mathematics scores and dissociation with the visuo-spatial condition. The visuo-spatial condition in Experiment 2 was identical to that used in Experiment 1 to see whether the result that mathematicians have superior visuo-spatial working memory storage capacity could be replicated in a new sample. In the number condition, the span lengths used were increased to spans 3 to 8 to investigate whether ceiling effects present in the number condition had impacted the results of Experiment 1.

Based on previous research, we predicted that visuo-spatial short-term memory capacity would correlate with calculation skill (Wei et al., 2012). Mathematics students were also predicted to have superior endogenous spatial attention (Astle & Scerif, 2011; Awh et al., 1998; Awh et al., 2006; Gazzaley & Nobre, 2012). Finally, it was expected that mathematics students would still have greater visuo-spatial working memory capacity when short-term memory and endogenous attention skills were controlled for because working memory measures that involve both processing and storage are generally deemed better predictors of mathematics achievement than more basic storage-only measures (Bayliss et al., 2003; St. Clair-Thompson & Sykes, 2010). In line with Experiment 1, no difference in working memory capacity for numbers was expected between the groups.

Experiment 2

Method

Participants

54 new participants were recruited from undergraduates at the University of Nottingham: 27 (9 male) to a mathematics students group and 27 (9 male) to a humanities students group. Participants gave written informed consent and received an inconvenience allowance of £6. The study was conducted in accordance with the BPS' Code of Human Research Ethics.

The mathematics students group comprised 15 mathematics students and 12 economics students who had studied mathematics at A level. Their ages ranged from 18.66 to 36.89 years (*M* = 20.88, *SD* = 3.53). The humanities students group comprised English, History, Philosophy and Sociology students who had not studied mathematics at A level. Their ages ranged from 18.78 to 22.68 years (*M* = 20.33, *SD* = .99). On average, participants in the humanities group had not studied mathematics for 4.18 years (*SD* = 1.16).

Equipment and Materials

Equipment was identical to that used in Experiment 1.

Working Memory Tasks

The working memory tasks in Experiment 2 were identical to those used in the number and visuo-spatial conditions of Experiment 1, with the exception that span lengths 3 to 8 were used for the number condition. Span lengths 2 to 7 were again used in the visuo-spatial condition.

Short-Term Memory Task

This task consisted of a series of sequentially presented visuo-spatial storage elements. The format and timings of the task were identical to those of the working memory tasks, except that it consisted solely of to-be-remembered storage items, with no processing element.

Endogenous Spatial Attention Task

Endogenous spatial attention was measured via a basic Posner task (Posner, 1980) which recorded time taken to respond to the appearance of a target stimulus that was preceded by a central cue. The cue either indicated the position of the target (valid cue) or directed controlled attention in the opposite direction (invalid cue) (Doricchi, Macci, Silvetti, & Macaluso, 2010). Participants were expected to respond faster to valid than to invalid cues. The difference in RTs between responses to targets preceded by valid cues and those preceded by invalid cues was taken as a measure of endogenous spatial attention.

The on-screen display consisted of a central cueing stimulus (a diamond shape, 1.3cm wide) and peripheral squares to the left and right (1cm wide), centred at 7cm eccentricity, inside which a target 'x' appeared (size

1cm). Initial instructions told participants to stare only at the central cue and not to move their eyes, and to respond to the appearance of target stimuli in the peripheral squares as quickly and accurately as possible by pressing the space bar on the keyboard using their right index finger. On valid and invalid trials, one side of the central diamond cue was highlighted, acting as an arrow towards one of the boxes (valid: same side; invalid: opposite side). On neutral trials, both sides of the central cue lit up. Targets appeared on the right 50% of the time for each cue type. A total of 36 neutral trials, 36 invalid trials and 144 valid trials were used. The 216 trials were split into 3 identical blocks of 72 trials. The order of trials was random within each block and across participants. All cues lit up for 100ms and targets followed cue offsets at stimulus-onset asynchronies (SOA) of 200, 400 or 800ms (Gitelman et al., 1999; Kim et al., 1999; Nobre et al., 1997). Targets were also displayed for 100ms. Each of the three SOAs was used in equal proportions within the neutral, valid and invalid trial types. All trials had a total duration of two seconds.

Additional Materials

WASI Matrix Reasoning and Woodcock-Johnson Calculation Test were administered as in Experiment 1.

Procedure

All participants were tested individually by the same experimenter and each session lasted around one hour. After completion of the working memory span tasks, participants completed the short-term memory task, followed by the attention task. For the short-term memory task, after reading initial instructions, participants completed a practice of one 2-span set and one 3-span set, before the test sets were presented. For the endogenous spatial attention task, after initial instructions, participants practiced the task for 22 randomly presented trials. They then viewed a screen which repeated the initial instructions, before commencing the three blocks of experimental trials. A short break was allowed between blocks if required. At the end of the task, participants were asked to self-rate for what extent of the time they had kept their gaze fixed on the central cue as instructed, using the numeric keypad, on a scale of 1 to 5, where 1 was ‘hardly any’ and 5 was ‘almost all’. Finally, participants completed Matrix Reasoning followed by the Calculation Test.

Results

Three participants (2 mathematics students group; 1 humanities students group) were excluded from the analyses for having an unacceptably high (>15%) error rate in the processing element of the working memory tasks leaving data for 25 (9 male) participants in the mathematics students group and 26 (9 male) in the humanities students group.

Standardized Tests

An independent *t*-test to compare the two groups’ Woodcock-Johnson Calculation Test scores confirmed that the mathematics students group (M = 35.80, SD = 3.50) were significantly better at mathematics than the humanities students group (M = 23.15, SD = 3.46), $t(49) = 12.97$, $p < .001$, $r = .88$.

An independent *t*-test showed that the mathematics students group (M = 28.92, SD = 2.41) had significantly higher scores for WASI Matrix Reasoning than the humanities students group (M = 26.88, SD = 3.25), $t(49) = 2.53$, $p = .015$, $r = .34$, suggesting a higher nonverbal IQ. All analyses were therefore initially run controlling for WASI Matrix Reasoning scores. This made no difference to main effects or interactions, therefore the results reported below do not control for WASI Matrix Reasoning scores.

Storage Element of Working Memory Tasks

Proportion correct scores were calculated for each participant for the number of storage items recalled in their correct serial position. Before conducting the main ANOVA, scores were examined for the two groups in the number span condition for span lengths 3 to 8, to check for ceiling effects. Mean proportion correct scores (mathematics students: M = .88, SD = .08; humanities students: M = .87, SD = .05) clearly showed that neither group was performing at ceiling and showed no significant difference in proportion correct scores between the two groups, U = 323.00, Z = -.04, p = .974. Only one participant in each group answered all items correctly.

A 2 (group: mathematics, humanities) x 2 (working memory storage type: number, visuo-spatial) mixed ANOVA was then performed on the proportion correct scores using span lengths 3 to 7 for both conditions. Descriptive statistics are shown in Figure 2b. There was a main effect of group, with mathematics students scoring higher overall, $F(1,49)$ = 8.90, p = .004, r = .39. There was also a main effect of storage type, with performance for number span greater than that for visuo-spatial span, $F(1,49)$ = 29.50, p < .001, r = .61. There was also a group x storage type interaction, $F(1,49)$ = 24.09, p < .001, r = .57. Tests of simple main effects showed that the mathematics students group had significantly greater visuo-spatial span scores than the humanities students group, $F(1,40)$ = 19.94, p < .001, r = .54, but there was no significant difference in performance between the two groups for number span $F(1,49)$ = 0.07, p = .788, r = .04. Visuo-spatial span scores also did not correlate with number span scores, r_s = .17, p = .245.

There was a significant correlation between participants' visuo-spatial span performance and their Woodcock-Johnson Calculation scores r_s = .57, p < .001. Number span did not correlate significantly with Calculation scores r_s = .04, p = .763.

To further explore the presence or lack of group differences for spatial and number storage span scores we conducted a series of Student's t-tests to test for differences between and equivalence of group mean scores (Lakens, 2017). To test for group equivalence, we used the two one-sided test (TOST) procedure and set equivalence bounds of raw score differences of -.05 and .05 (i.e. groups means were treated as equivalent if mathematicians' scores were less than 5% above or below non-mathematicians' scores). For visuo-spatial span scores, the t-test for group difference was significant, $t(49)$ = 4.49, p < .001, and the equivalence t-test was non-significant, $t(49)$ = 2.72, p = .995. For number span scores, the t-test for group difference was non-significant, $t(49)$ = -0.26, p = .799 and the equivalence t-test was significant, $t(49)$ = 2.30, p = .013. In other words, there is evidence that the groups differed in their visuo-spatial span scores and there is evidence that the groups were equivalent in their number span scores.

Bayesian analysis was also conducted to examine the presence or lack of group differences for number and visuo-spatial storage span scores. The analysis was conducted using default prior in JASP to conduct simple Bayesian t-tests for group differences in correct scores for the different conditions. There was moderate evidence for the null hypothesis that the mathematics and humanities groups were the same in the number (BF_{10} = 0.289) condition. There was, however, extreme evidence for the alternative hypothesis, that the mathematics and humanities groups were different in the visuospatial condition (BF_{10} = 424.547).

Processing Element of Working Memory Tasks

Mean accuracy and median RT on the face-matching task were calculated for each participant in each of the two working memory span conditions over span lengths 3 to 7, and analyzed with separate.2 (group: mathematics, humanities) x 2 (working memory storage type: number, visuo-spatial) mixed ANOVAs (see Table 1 for descriptive statistics). There was no significant difference in accuracy or RT for the face-matching task between groups or across the different storage conditions (all $F < 1.25$, ns).

Short-Term Memory Task

Proportion correct scores were calculated for each participant for the number of storage items recalled in their correct serial position. There was no significant difference in performance between the mathematics students ($M = .88$, $SD = .06$) and the humanities students ($M = .85$, $SD = .08$), $U = 234.00$, $Z = -1.72$, $p = .086$, $r = .25$. A non-parametric test was used because both groups' scores showed significant negative skew.

Endogenous Spatial Attention Task

Median RTs were calculated for each participant for each of neutral, valid and invalid trials, before calculating the difference between their invalid and valid RTs (endogenous spatial attention). Participants reported they had kept their gaze fixed centrally, as required, on the majority of trials (mathematics group: $M = 4.63$, $SD =$ 0 .74; non-mathematics group: $M = 4.70$, $SD = 0.67$). There was no significant difference between mathematics students ($M = 326$, $SD = 40$) and humanities students ($M = 316$, $SD = 38$) for reaction times to respond to valid trials, $U = 25.50$, $Z = -.74$, $p = .463$. An independent *t*-test compared the endogenous spatial attention skills of the two groups (invalid RTs minus valid RTs: mathematics group: 25, $SD = 24$; humanities group: $M = 28$, $SD =$ 23) and, again, no significant difference was found, $t(49) = 0.91$, $p = .367$, $r = .13$.

Group Differences in Visuo-Spatial Working Memory When Controlling for Short-Term Memory and Attention Skills

An ANCOVA was run to investigate whether mathematics students had greater visuo-spatial working memory storage capacity when controlling for short-term memory performance and endogenous spatial attention. Results showed the covariate visuo-spatial short-term memory was significantly related to visuo-spatial working memory $F(1,47) = 13.58$, $p = .001$. The covariate endogenous spatial attention was not significantly related to visuo-spatial working memory, $F(1,47) = 1.61$, $p = .210$. When controlling for visuo-spatial short-term memory and endogenous spatial attention, the mathematics students still had significantly greater visuo-spatial working memory scores than the humanities students, $F(1, 47) = 15.54$, $p < .001$, $r = .50$.

Discussion

In a new sample of participants we replicated our finding of greater visuo-spatial working memory storage capacity in mathematics student**s** compared with humanities students with an even larger effect size. Furthermore, visuo-spatial working memory storage scores again correlated strongly with Woodcock-Johnson Calculations scores ($r = .57$). The results of both Experiments 1 and 2 suggest visuo-spatial working memory storage capacity is linked to mathematics.

As predicted, results of the ANCOVA showed that, when controlling for visuo-spatial short-term memory scores and endogenous spatial attention, there was still a large difference between mathematics students and humanities students in the ability to store visuo-spatial information in working memory. This therefore suggests it is the ability to hold visuo-spatial information in mind whilst carrying out processing, rather than more simple storage or endogenous attention, that underlies the link with mathematics. This pattern of results supports the previous finding that working memory skills are more predictive than short-term memory skills of complex cognitive processes (Bayliss et al., 2003; St. Clair-Thompson & Sykes, 2010).

Experiment 3

Experiments 1 and 2 involved working memory span tasks with a processing element that was as neutral as possible with regard to the storage elements. This enabled the examination of capacity for the verbal and visuo-spatial storage elements using a consistent processing element across the tasks in both domains. It also ensured that, as far as possible, the processing element did not interfere with storage in one domain more than in the other. However, previous research has shown that the domain of the processing element affects the number of verbal and visuo-spatial items that can be stored and the relationship between working memory capacity and more complex cognition (Jarrold et al., 2011; Shah & Miyake, 1996; Vergauwe et al., 2010). Experiment 3 therefore combined verbal and visuo-spatial processing with verbal and visuo-spatial storage. This allowed us to test whether mathematics students always have superior visuo-spatial storage ability while using working memory or whether this depends upon the type of processing being carried out. It also examined whether mathematics students' apparent superior capacity for storing visuo-spatial information in working memory is simply due to a greater ability to deal with visuo-spatial information.

Experiment 2 ruled out the possibility that short-term memory and endogenous spatial attention were driving group differences in visuo-spatial working memory. A further possibility is that the visuo-spatial working memory difference stems from differences in general ability for dealing with visuo-spatial information. Wei et al. (2012) found both visuo-spatial storage capacity and general visuo-spatial skills, measured by a 3-dimensional spatial rotation task, correlated with mathematics performance in Chinese college students. However, they did not examine whether the relationship between visuo-spatial storage ability and mathematics could be explained by general visuo-spatial skills. Previous research has implicated the use of general visuo-spatial resources in the solving of mathematical problems (Delgado & Prieto, 2004; Friedman, 1995; Jiang, Cooper, & Alibali, 2014; Landy, Brookes, & Smout, 2014; Marghetis, Núñez, & Bergen, 2014; Pinhas, Shaki, & Fischer, 2014; Wiemers, Bekkering, & Lindemann, 2014). Casey, Nuttall, Pezaris, and Benbow (1995) and Casey, Nuttall, and Pezaris (1997) found links between mental rotation ability and scores on the SAT-M math test, whilst Geary, Saults, Liu, and Hoard (2000) found mental rotation was related to arithmetical reasoning ability. It is therefore plausible that a generally enhanced ability for dealing with visuo-spatial information could underpin mathematics students' superior visuo-spatial working memory as well as drive the relationship between visuo-spatial storage ability and performance on the Calculation test.

To determine whether mathematics students possess greater visuo-spatial skills, participants' performance was compared on the *Revised Vandenberg & Kuse Mental Rotations Test: MRT-A* (Peters, Chisholm, & Laeng, 1995), which has been used across a range of subject literature as a measure of general visuo-spatial processing (e.g. Hausmann, Slabbekoorn, Van Goozen, Cohen-Kettenis, & Güntürkün, 2000; Hedman et al., 2006; Langlois et al., 2009). Performance of the mathematics students and humanities students was also compared for the processing elements of the working memory span tasks, which provided another measure of general visuo-spatial processing skills.

On the basis of Experiments 1 and 2 we predicted that mathematics students would remember more items in their correct serial position in the two working memory span task conditions involving visuo-spatial storage, regardless of the domain of the processing. It was predicted that there would be no difference between the performance of the two groups in the verbal processing & verbal storage condition. No firm prediction was made regarding differences in the visuo-spatial processing & verbal storage condition. It was also expected that mathematics students would perform better than humanities students for general visuo-spatial skills as measured by scores for the MRT-A, and faster and more accurately for the visuo-spatial processing elements of the span tasks (e.g. Delgado & Prieto, 2004; Wei et al., 2012). It was expected there would be no difference between the two groups for verbal processing. Finally, it was predicted that mathematics students would still have greater visuo-spatial working memory capacity than humanities students after controlling for visuo-spatial processing ability, because of the view that complex span tasks are better predictors of cognitive ability than measures of more basic skills (Bayliss et al., 2003; St. Clair-Thompson & Sykes, 2010).

Method

Participants

57 new participants were recruited from the undergraduate population at the University of Nottingham: 28 (11 male) to a mathematics students group and 29 (7 male) to a humanities students group. All participants gave written informed consent and received an inconvenience allowance of £9. The study was conducted in accordance with the BPS' Code of Human Research Ethics. The mathematics students group comprised 20 mathematics students and 8 economics students who had studied mathematics at A level. Their ages ranged from 18.68 to 32.56 years (*M* = 20.83, *SD* = 2.68). The humanities students group comprised English, History, and Sociology students who had not studied mathematics at A level. Their ages ranged from 18.76 to 31.70 years (*M* = 20.63, *SD* = 2.51). On average, participants in the humanities students group had not studied mathematics for 4.22 years (*SD* = 1.39).

Equipment

An Acer Aspire 5736Z laptop computer, running Windows 7 and PsychoPy2 version 1.77.01 (Peirce, 2007), was used to present stimuli and record latencies and accuracy.

Working Memory Tasks

There were four span tasks. Each had a different combination of interweaved processing and storage elements: verbal processing & verbal storage; verbal processing & visuo-spatial storage; visuo-spatial processing & verbal storage; and visuo-spatial processing & visuo-spatial storage. Timings used were identical to those used in the working memory span tasks of Experiments 1 and 2.

The visuo-spatial processing task was adapted from one used by Miyake et al. (2001) and employed spatial visualization. Participants saw two pictures on screen, side by side. The picture on the left of each pair represented a piece of paper folded in half with a hole punched in it. Participants had to imagine opening out this piece of paper towards the dotted lines shown. They then indicated whether or not the unfolded paper would look like the picture on the right of the pair, by pressing the 'y' key on the laptop's keyboard for yes or the 'n' key for no.

The verbal processing task was a word rhyming judgement task (e.g. Baldo & Dronkers, 2006; Gathercole, Alloway, Willis, & Adams, 2006). Participants saw two English words on screen, side by side. They had to indicate whether or not the two words rhymed, by pressing the ‘y’ key for yes or the ‘n’ key for no.

Two blocks of unique visuo-spatial processing items and verbal processing items were created. A pilot study was conducted to confirm no difference in difficulty of the four blocks of processing items. Each processing block was then assigned to one of the working memory span task conditions. The storage items of each span task consisted either of the same numbers or visuo-spatial items as in Experiment 2. Presentation of trials and recording of responses were the same as in the previous two experiments. Span sets, and items within them, were presented in a random order. In all four conditions, each span length from 3 to 8 was presented three times, giving 18 trials. Each of the nine possible storage items within each condition was presented approximately equally.

Additional Materials

The Woodcock-Johnson Calculation Test and WASI Matrix Reasoning were again administered. Participants also completed the Revised Vandenberg & Kuse Mental Rotations Test: MRT-A (Peters et al., 1995) as a measure of general visuo-spatial skills.

Procedure

All participants were tested individually by the same experimenter and each session lasted around 90 minutes. Participants completed the four working memory span tasks on the computer, for each span length 3 to 8. The order in which the four conditions were presented was counterbalanced. and it was ensured the same processing task was not presented in consecutive tasks.

For their first and second span tasks, each participant practiced the relevant processing task. After initial instructions, participants made yes or no judgements for six items, so they could familiarize themselves with the task. They then began the experiment. They commenced with a practice of one 2-span set and one 3-span set comprising both processing and storage tasks, before the 18 test sets were administered. For their third and fourth span tasks, participants followed the same procedure as described for the first and second span tasks, but omitting the initial practice of the processing element as they were already familiar with it. After completing all four span tasks, they completed the Matrix Reasoning and MRT-A tests, the order of which was counterbalanced across participants. Finally, participants completed the Calculation Test.

Results

One female participant in the humanities students group was excluded from the analyses due to software failure in one of the conditions. Six participants (1 mathematics group; 5 humanities group) were also excluded for having an unacceptably high (>15%) error rate in the processing task, leaving data for 27 (10 male) participants in the mathematics students group and 23 (7 male) in the humanities student group available.

Standardized Tests

An independent t-test to compare Calculation Test scores confirmed the mathematics students group (M = 37.70, SD = 3.56) was significantly better at mathematics than the humanities students group (M = 25.57, SD = 4.86), $t(48) = 12.14$, $p < .001$, $r = .87$. Mathematics students (M = 12.30, SD = 4.83) performed better on the MRT-A test of general visuo-spatial skills than the humanities students (M = 9.09, SD = 4.44), $t(48) = 2.43$,

p = .019, r = .33. There was a significant correlation between MRT-A scores and calculation scores, r = .46, p = .001. There was no significant difference between the two groups for Matrix Reasoning (mathematics: M = 29.04, SD = 3.60; humanities: M = 27.52, SD = 3.20), t(48) = 1.56, p = .125, r = .22.

Storage Element

Proportion correct scores were calculated for each participant for the number of storage items recalled in their correct serial order. A 2 (group: mathematics, humanities) x 2 (working memory processing type: verbal, visuo-spatial) x 2 (working memory storage type: verbal, visuo-spatial) mixed ANOVA was performed on the proportion correct scores. Descriptive statistics are shown in Figure 2c. There was no main effect of group, F(1,48) = 1.08, p = .304, r = .15. There was, however, a main effect of storage type, F(1,48) = 31.21, p < .001, r = .63, with storage of verbal items more accurate overall than storage of visuo-spatial items. In contrast to Experiments 1 and 2 there was no storage type x group interaction, F(1,48) = 0.02, p = .882, r = .02. There was also a main effect of processing type, F(1,48) = 8.13, p = .006, r = .38, with storage performance better overall when combined with verbal processing than with visuo-spatial processing. There was no processing type x group interaction, F(1,48) = 0.01, p = .909, r = .01. There was, however, a processing type x storage type interaction, F(1,48) = 47.76, p < .001, r = .71 (Figure 3). Pairwise comparisons showed visuo-spatial storage was more accurate when paired with verbal processing than with visuo-spatial processing, F(1,48) = 39.98, p < .001, r = .67. However, verbal storage was more accurate when paired with visuo-spatial processing than with verbal processing, F(1,48) = 20.35, p < .001, r = .55. Finally, there was no processing type x storage type x group interaction, F(1,48) = .48, p = .492, r = .10.

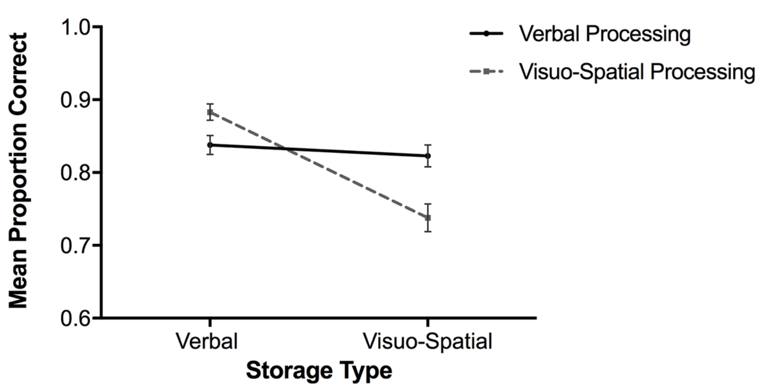

Figure 3. Storage accuracy for each processing condition in Experiment 3. Error bars represent the standard error.

To further explore the presence or lack of group differences for storage span scores we conducted a series of Welch's t-tests (allowing for unequal variance due to unequal group sizes) to test for differences between and equivalence of group mean scores (Lakens, 2017). To test for group equivalence, we used the two one-sided test (TOST) procedure and set equivalence bounds of raw score differences of -.05 and .05 (i.e. groups means were treated as equivalent if mathematicians' scores were less than 5% above or below non-mathematicians' scores). For verbal processing and verbal storage span scores, Welch's t-test for group difference was non-significant, t(39.38) = 0.58, p = .562, and Welch's equivalence t-test was also non-significant, t(39.38) = -1.24, p = .110. For verbal processing and spatial storage span scores, Welch's t-test for group difference was non-significant, t(33.93) = 0.98, p = .335, and Welch's equivalence t-test was also non-significant, t(33.93) = -0.50, p = .309. For spatial processing and verbal storage span scores, Welch's t-test for group difference was non-significant, $t(38.39) = 1.14$, $p = .262$, and Welch's equivalence *t*-test was also non-significant, $t(38.39) = -0.97$, $p = .169$. For spatial processing and spatial storage span scores, Welch's *t*-test for group difference was non-significant, $t(35.52) = 0.46$, $p = .651$, and Welch's equivalence *t*-test was also non-significant, $t(38.39) = -0.97$, $p = .169$. In other words, there is insufficient evidence that the groups either differed or that the groups were equivalent in span scores. Therefore, we can only conclude that the effects were undetermined (Lakens, 2017).

Bayesian analysis was also conducted to examine the presence or lack of group differences for the verbal and visuo-spatial storage span scores. The analysis was conducted using default prior in JASP to conduct simple Bayesian *t*-tests for group differences in correct scores for the different conditions. There was anecdotal evidence for the null hypothesis that the mathematics and humanities groups were the same in each of the storage conditions (verbal processing, verbal storage $BF_{10} = 0.336$; verbal processing, visuo-spatial storage $BF_{10} = 0.446$; visuo-spatial processing, verbal storage $BF_{10} = 0.539$; visuo-spatial processing, visuo-spatial storage $BF_{10} = 0.35$). So, there was no strong evidence that the groups were either different or the same.

Processing Element

Mean accuracy and median RT were calculated for each participant in each of the four working memory span conditions. A 2 (group: mathematics, humanities) x 2 (working memory processing type: verbal, visuo-spatial) x 2 (working memory storage type: verbal, visuo-spatial) mixed ANOVA was performed for each of accuracy and latencies to examine performance of the two groups on the processing element of each condition. Mean accuracy, mean RT and standard error by group and span type are shown in Table 2.

Table 2

Mean (M) and Standard Error (SE) for Accuracy and Reaction Time for the Processing Tasks by Group and Storage Type Condition (Experiment 3)

	Accuracy (Pc)		Reaction Time (ms)	
Group	***M***	***SE***	***M***	***SE***
Processing Condition/Storage Condition: Verbal/Verbal				
Mathematics	.97	.01	1254	46
Humanities	.97	.01	1229	55
Processing Condition/Storage Condition:Verbal/Visuo-spatial				
Mathematics	.97	.01	1347	56
Humanities	.97	.01	1306	56
Processing Condition/Storage Condition:Visuo-spatial/Verbal				
Mathematics	.97	.01	1225	45
Humanities	.97	.01	1354	60
Processing Condition/Storage Condition: Visuo-spatial/Visuo-spatial				
Mathematics	.97	.01	1388	50
Humanities	.95	.01	1576	103

Note. Pc = Proportion correct.

Results showed no significant difference in accuracy on the processing tasks between groups or across the different storage conditions (all $F < 2.8$, ns). There was also no main effect of group on latencies, $F(1,48) = 0.79$, $p = .379$, $r = .13$. There was, however, a main effect of processing type with verbal processing elements being answered faster than visuo-spatial processing elements, $F(1,48) = 13.63$, $p = .001$, $r = .47$. There was also a main effect of storage type, with the processing elements being answered faster overall when they were interleaved with verbal storage items compared to visuo-spatial storage items, $F(1,48) = 30.28$, $p < .001$, $r = .62$. There was a significant group x processing type interaction, $F(1,48) = 11.99$, $p = .001$, $r = .45$. Pairwise comparisons showed that, for the mathematics students group, there was no significant difference between latencies for the verbal and visuo-spatial processing items ($p = .866$), but that the humanities students were slower to perform visuo-spatial processing than they were to perform the verbal processing ($p < .001$). There was no significant group x storage type interaction, $F(1,48) = 0.79$, $p = .379$, $r = .13$, no significant processing type x storage type interaction, $F(1,48) = 3.54$, $p = .066$, $r = .26$ and no significant group x processing type x storage type interaction, $F(1,48) = 0.44$, $p = .511$, $r = .02$.

Regression Analysis to Predict Mathematics Calculation Scores

A regression was performed to discover whether visuo-spatial working memory storage capacity still uniquely and significantly predicted Calculation scores when taking visuo-spatial processing and general visuo-spatial skills into account.

As mathematics students were faster than humanities students for the visuo-spatial processing task, but there was no significant difference between the two groups for accuracy, only processing RT was included in the regression as a measure of visuo-spatial processing. Because of a strong correlation between accuracy in the two conditions involving visuo-spatial storage ($r_s = .66$, $p < .001$) and the two conditions measuring visuo-spatial processing RTs ($r_s = .43$, $p = .002$), storage scores and processing RTs were combined across conditions. Calculation Test score was the dependent variable.

Table 3 shows results for the regression model when MRT-A scores, for general visuo-spatial skills, were entered into the model together with visuo-spatial processing RT at Step 1, followed by visuo-spatial working memory storage at Step 2. At Step 1, only MRT-A scores significantly and uniquely predicted calculation performance. When visuo-spatial working memory storage was added at Step 2, both MRT-A and storage predicted calculation performance and there was significant improvement in the fit of the model.

Table 3

Hierarchical Linear Regression Predicting Woodcock-Johnson Calculation Score by General Visuo-Spatial Processing (MRT-A), Visuo-Spatial Processing Latencies (RT) and Visuo-Spatial Working Memory (WM) Storage (Experiment 3)

Predictor	β
Step 1	
Constant	
MRT-A	.41**
Combined visuo-spatial processing RT	-.17
Step 2	
Constant	
MRT-A	.33*
Combined visuo-spatial processing RT	-.15
Combined visuo-spatial WM storage	.27*

Note. $R^2 = .24$ for Step 1 ($p = .002$). $\Delta R^2 = .06$ for Step 2 ($p = .045$).

*$p < .05$. **$p < .01$.

Comparison of Visuo-Spatial Working Memory Results From Experiments 2 and 3

Results from Experiment 3 supported the findings of Experiments 1 and 2 that there is no difference between mathematics and humanities students for verbal working memory storage capacity. However, a different pattern of results emerged for visuo-spatial working memory storage capacity. In Experiments 1 and 2, when the span tasks included the face-matching task as a processing element, which was as neutral as possible with respect to the storage elements, mathematics students were able to store more visuo-spatial items in working memory. In contrast, in Experiment 3, mathematics students showed no advantage for storing visuo-spatial information in working memory when storage was combined with either verbal or visuo-spatial processing. Across the three experiments, it therefore appears that, whilst participants overall found visuo-spatial storage harder when combined with visuo-spatial processing and easier when combined with verbal processing, the mathematics students found it easier than the humanities students to store visuo-spatial information when combined with the neutral as possible face-matching processing task. To discover whether these assertions were correct, visuo-spatial working memory scores from Experiment 2, with neutral as possible processing, were compared to scores for the two visuo-spatial working memory tasks in Experiment 3.

A 2 (group: mathematics, humanities) x 3 (processing type: neutral, verbal, visuo-spatial)[iii] ANOVA was performed on the visuo-spatial proportion correct scores. Descriptive statistics are shown in Figure 2d.

There was a main effect of group, $F(1,145) = 10.08$, $p = .002$, $r = .25$, with the mathematics students having better visuo-spatial storage scores overall. The type of processing element significantly affected visuo-spatial storage ability, as there was also a main effect of processing type, $F(2,145) = 11.28$, $p < .001$, $r = .27$. Pairwise comparisons showed that visuo-spatial storage scores were greater overall when storage was combined with neutral processing than with visuo-spatial processing ($p < .001$) and greater with verbal processing than with visuo-spatial processing ($p < .001$). Storage scores were no different between the conditions using neutral and verbal processing ($p = 1.00$). There was a group x processing type interaction, $F(2,145) = 3.34$, $p = .038$, $r = .15$. Tests of Bonferroni-corrected simple main effects demonstrated that for the mathematics students, visuo-spatial storage scores varied depending on the processing type, $F(2,145) = 12.10$, $p < .001$, $r = .28$. Pairwise comparisons showed that visuo-spatial storage scores were greater when storage was combined with neutral processing ($p < .001$), or verbal processing, ($p = .011$) than with visuo-spatial processing. Storage scores were no different between conditions using neutral and verbal processing ($p = .143$). For the humanities students, there was no significant difference in visuo-spatial storage between any of the three conditions (all *p*s > .05). The mathematics students were better than the humanities students at storing visuo-spatial information when storage was combined with the neutral processing task, $F(1, 145) = 15.65$, $p < .001$, $r = .31$. However, there was no significant difference between the two groups for visuo-spatial storage when it was combined with verbal processing, $F(1, 145) = 0.97$, $p = .328$, $r = .08$ or visuo-spatial processing, $F(1, 145) = .35$, $p = .557$, $r = .05$.

Discussion

Experiment 3 employed working memory span tasks using verbal and visuo-spatial processing elements to investigate whether the type of processing involved affected the ability of adult mathematics and humanities students to store verbal and visuo-spatial information whilst using working memory. It also investigated whether there was any difference in storage capacity or processing ability between these two groups. Contrary to predictions, the results showed extremely small and non-signfiicant differences between mathematics and humanities students for working memory storage capacity for any of the combinations of verbal and visuo-spatial processing and storage. It should be noted, however, that the tests for equivalence and Bayesian analysis (Section 4.2.2) were inconclusive and we were therefore unable to use them to confirm no group differences. Replication with a larger sample size is therefore necessary to confirm these results. Comparison of results between Experiment 2 and Experiment 3 suggested that mathematics students have superior ability to store visuo-spatial information in working memory when the processing involved is as neutral as possible, but not when the processing is either verbal or visuo-spatial. Results of Experiment 3 also showed that mathematics students were faster to perform the visuo-spatial processing element of the working memory span tasks. There was a moderate difference between groups on the measure of general visuo-spatial skills, with mathematics students scoring on average 3 points higher than the humanities students. Moreover, both general visuo-spatial skills and visuo-spatial storage within working memory were able to uniquely predict mathematics calculation ability.

General Discussion

These three experiments have shown that adult mathematics students demonstrate superior visuo-spatial working memory capacity to humanities students (Experiments 1 and 2), albeit only under certain conditions (Experiment 3). Moreover, this superior visuo-spatial working memory capacity cannot be explained by superior short-term memory, endogenous spatial attention or general visuo-spatial skills. We have also demonstrated for the first time that both visuo-spatial working memory capacity and general visuo-spatial skills can significantly and uniquely predict mathematics performance in adults.

The comparison of results across the three working memory processing types indicated that, overall, participants found visuo-spatial storage more difficult when it was combined with visuo-spatial processing than with verbal or neutral as possible processing. However, there was a large difference between the groups in storing visuo-spatial information when it was combined with neutral as possible processing, whereby mathematics students were around 10-15% more accurate than the humanities students. The participant profiles of the mathematics and humanities groups used across the experiments were very similar and therefore unlikely to account for the differences in visuo-spatial working memory performance between experiments. Therefore, the only substantial differences between the methods employed were the types of processing elements included in the working memory span tasks. This explanation is consistent with previous research showing the type of processing element influences the relationship between performance on working memory tasks and higher-level cognitive tasks (Jarrold et al., 2011; Shah & Miyake, 1996; Vergauwe et al., 2010).

As well as differing according to content domain, it has also been argued that processing tasks differ according to their level of central executive involvement. Miyake et al. (2001) carried out a latent variable analysis and fractionated visuo-spatial processing tasks into three types: *perceptual speed*; *spatial relations*; and *spatial visualisation*. *Perceptual speed* involves the efficiency with which an individual can make basic perceptual judgements and involves visual comparisons rather than spatial manipulations. *Spatial relations* involves transformations, such as the rotation of objects. Finally, *spatial visualization* requires complex mental manipulation of spatial objects.

The face-matching task used in Experiments 1 and 2 was a form of perceptual speed task. It comprised basic visual comparison with little spatial content and therefore had a low level of central executive involvement. In contrast, the paper folding task used in the visuo-spatial processing condition of Experiment 3 was a spatial visualization task, according to the Miyake et al. (2001) taxonomy, and consequently involved a higher level of central executive resources. In the visuo-spatial processing condition, with a high central executive load, there was no difference between the mathematics and humanities students. In contrast, with the neutral as possible, face-matching task which had low central executive demands, the mathematics students had greater visuo-spatial storage capacity. Furthermore, the mathematics students showed moderately better visuo-spatial storage capacity in the neutral condition compared to the visuo-spatial processing condition, while for the humanities students there was no difference in storage capacity between the two. One possible explanation is that humanities students have a lower visuo-spatial central executive capacity than the mathematics students. The processing task with high central executive demands used up this capacity in both groups, whereas with the low central executive processing task the mathematics group were able to take advantage of extra resources and consequently could store more items.

The fact that the mathematics students only have superior ability to store visuo-spatial information when more working memory resources were available in the neutral as possible processing condition is relevant in terms of performing mathematics. If mathematicians are more efficient at remembering and applying calculation strategies (Dowker, Flood, Griffiths, Harriss, & Hook, 1996; Pesenti, 2005), which requires visuo-spatial working memory, they will have greater resources available to hold, visualize and manipulate numbers during calculation (Geary, 2004; Heathcote, 1994; Logie et al., 1994; Seron, Pesenti, Noël, Deloche, & Cornet, 1992).

The fact that mathematics students had superior visuo-spatial working memory capacity only when the central executive resources involved in processing were comparatively low might lead to the expectation that they would also have superior visuo-spatial short-term memory scores when no processing was present. This did not appear to be the case however. When visuo-spatial short-term memory performance was compared in Experiment 2, the effect size was much smaller than the difference in visuo-spatial working memory capacity, and there was no significant difference between mathematics and humanities students. We see two possible explanations for this. Firstly, whilst the short-term memory task involved no processing, the working memory task required constant switching between the processing and storage elements of the task. It may be that the mathematics students' skills lay in combining the processing and storage demands. They may have used central executive resources more efficiently than the non-mathematicians in the neutral as possible processing condition, which resulted in a greater availability of working memory resources to store visuo-spatial information. The large central executive load in the visuo-spatial processing condition of Experiment 3 may have caused this advantage in central executive efficiency to disappear. Alternatively, it may in fact be the case that mathematics students also have better visuo-spatial short-term memory than humanities students, but that this was not found in Experiment 2 due to a lack of power. The difference between the groups was approaching significance (p = .086) using a non-parametric test. Mathematics students showed moderately superior general visuo-spatial skills compared to the humanities students. Moreover, general visuo-spatial skill was a significant independent predictor of mathematics performance. This is in line with previous findings that general visuo-spatial processing has a role in complex mathematics such as algebra (Landy et al., 2014) and interpreting graphs (Hegarty & Waller, 2005), arithmetical reasoning (Geary et al., 2000) and generally in mathematics (Casey et al., 1995; Casey et al., 1997; Friedman, 1995). The finding that visuo-spatial working memory storage capacity also significantly and uniquely predicted calculation even after general visuo-spatial skills were accounted for suggests that the mathematics students' superior capacity cannot simply be explained by a better general ability to deal with visuo-spatial information but that the two skills accounts for separate variance in mathematics performance.

Whilst verbal working memory is involved in mathematics (e.g. Bayliss et al., 2003; Friso-van den Bos et al., 2013; Fürst & Hitch, 2000; Imbo & Vandierendonck, 2007; Logie et al., 1994; Östergren & Träff, 2013), we found no difference in verbal working memory capacity between mathematics and humanities students in Experiments 1 and 2, and no evidence for or against a difference in Experiment 3. The majority of evidence for a link between verbal working memory and mathematics comes from research with children; therefore, it may be that the role of verbal working memory in supporting mathematics decreases with age. Alternatively, the studies with adults that do find a relationship with verbal working memory investigate it within the context of arithmetic (Fürst & Hitch, 2000; Imbo & Vandierendonck, 2007; Logie et al., 1994). This suggests verbal working memory may play a role in supporting basic arithmetic but is not as important for the more advanced forms of calculation measured within the current experiments (e.g. matrices, integration and trigonometry). However, the mathematics assessment used throughout this study had a low verbal load. With a more verbal mathematics task, we may have found a different pattern of relationships between mathematics and verbal storage.

In summary, our results show that mathematics students demonstrate enhanced visuo-spatial working memory capacity under conditions of low central executive load, as well as superior general visuo-spatial skills. These group differences in visuo-spatial working memory capacity were not explained by differences in short-term memory, endogenous attention or general visuo-spatial skills. There was no difference between mathematics and humanities students for the amount of verbal information that can be stored within working memory. Moreover, both visuo-spatial working memory capacity and general visuo-spatial skills predicted mathematics achievement in adults. Taken together, while we are not able to make inferences about the direction of causality, the results point to a strong link between individual differences in visuo-spatial working memory capacity and mathematics performance in adults. The implications of this are that the more practiced and proficient an individual is at selecting appropriate strategies and following relevant mathematical procedures, the lower the load on the central executive and the more resources the individual will have available for mentally performing calculations and manipulating information. Longitudinal outcomes of gifted adolescents find that those with greater mathematical ability than verbal ability at age 13 are more likely to complete degrees in a STEM subject than a humanities subject (Park, Lubinski, & Benbow, 2007). Taken together with the findings from Dark and Benbow (1990, 1991) this suggests that enhanced working memory skills are present prior to undergraduate study. Further research with both adults and children is still required to determine whether good visuo-spatial working memory skills support the acquisition of advanced mathematics and/or whether mathematics training enhances working memory skills (cf. the Theory of Formal Discipline; Inglis & Attridge, 2017). Nevertheless, this research indicates that multi-component models of mathematical processing developed from research with children can also be applied as a framework to study adults and should include working memory, particularly in the visuo-spatial domain.

Notes

i) These experiments also form part of the first author's doctoral thesis (Hubber, 2015).

ii) In the UK, university students specialize in one subject from the start of their degree and so only study one subject in any depth. Difference in mathematics ability between the two groups was also confirmed through use of the Woodcock Johnson Calculation test.

iii) Here processing type was treated as a more-conservative between-groups factor despite performance on the verbal and visuo-spatial conditions coming from the same participants.

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Competing Interests

The authors have declared that no competing interests exist.

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The authors have no support to report.

Data Availability

For this study a dataset is freely available (see the Supplementary Materials section).

Supplementary Materials

The underlying data for all three experiments are available from https://osf.io/waqvk

Index of Supplementary Materials

Hubber, P. J., Gilmore, C., & Cragg, L. (2018). *Verbal and visuospatial working memory in mathematics and humanities students* [Data and task descriptions]. OSF. https://osf.io/waqvk

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