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The role of working memory slave systems in children's addition

Paulina Walukiewicz

Supervised by: Joni Holmes

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## ABSTRACT

The current study used a dual-task design to investigate the roles of the phonological loop and visuo-spatial sketchpad components of working memory in children's addition. The aims of the experiment were to test whether concurrent visuo-spatial and phonological loop tasks disrupt performance on vertically or horizontally presented arithmetic tasks. Twenty-three 9- and 10-year old primary school children completed sixteen single and double digit additions on a computer under three conditions: baseline, concurrent visuo-spatial load or concurrent phonological load. The results revealed a non-significant effect of concurrent working memory load on mathematical task performance. However, the addition tasks significantly impaired the accuracy of recall on both visuo-spatial and phonological working memory tasks compared to baseline. This pattern of data suggests an active role of working memory in the multi-step process of solving simple addition problems in school children.



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| **KEY WORDS:** | **WORKING MEMORY** | **SLAVE SYSTEMS** | **CHILDREN'S ARITHMETIC** | **ADDITION** | **DUAL -TASK** |

## INTRODUCTION

Arithmetic is one of the key mathematical skills in everyday life that is taught from early childhood. Although the research suggests that even in the first week of life humans are capable of basic discrimination based on numerosity (Butterworth, 2005), it is also clear that proficiency in arithmetic emerges developmentally as a result of interaction with the environment. The processes underpinning mathematical cognition have been of interest to developmental and cognitive psychologists. As solving arithmetic problem involves information processing and storage, it was suggested that working memory (WM) processes play a substantial role in children's arithmetic performance (Adams & Hitch, 1997).

There are different theoretical perspectives on the construct of working memory (Miyake & Shah, 1999). Single-resource frameworks (e.g. Engle, Kane, Tuholski, 1999) have proposed that working memory is a system unitary in its nature. In this view, the modality-free storage and processing of information are interchangeable and compete for the same limited resource – controlled attention. On the contrary, the most widely-researched multiple resource framework (Baddeley & Hitch, 1974; Baddeley 1996; Baddeley & Logie, 1999) maintains that storage is functionally independent from processing. Baddeley and Logie (1999) multi-modal system of WM consists of a limited-capacity slave systems: phonological loop and visuo-spatial sketchpad (VSSP) responsible for a temporary storage and rehearsal of verbal and visuo- spatial material, respectively. In addition, Logie (1995) suggested that VSSP is comprised of a passive visual store (visual cache) and an active spatial store (inner scribe). The activity within the two slave systems is coordinated by a domain free processor – the Central Executive (CE). The central executive is responsible for a range of distinct processes including planning, switching, inhibition, dual-task performance and the activation of representations within the Long-Term-Memory (LTM; Baddeley, 1996, Miyake et al., 2000). More recently, in a revised WM model, Baddeley (2000) proposed a fourth component of WM- the episodic buffer, which is capable of storing information in multiple codes and provides an interface between the slave systems and episodic LTM. The empirical evidence in support of this component is limited (Baddeley, 2007). Furthermore, the revised WM model suggests that exogenous "crystallised" processes such as visual semantics, episodic LTM and language-base might scaffold the activity of the fluid VSSP and phonological loop. As a result, the multiple-resource concept of WM is based on a functional architecture, which is supported by the multi-faceted activity of the CE.

The basic tripartite structure of WM (Baddeley & Hitch, 1974; Baddeley & Logie, 1999, Baddeley, 2000) has been successfully applied to a practical study of human cognition across development starting from 4 years of age (Gathercole, Pickering, Ambridge & Wearing, 2004). Standardised measures of working memory storage and processing components are unique predictors of children's attainment in mathematics (Holmes & Adams, 2006) and English (Archibald & Gathercole, 2006). Substantial impairments in working memory are also implicated in individuals with general learning disabilities (Gathercole and Pickering, 2001) and domain -specific mathematical disabilities (Adams,2007). According to a recent review, each component of the original working memory model is thought to play a role in adult mathematical cognition, thereby supporting a range of discrete steps in calculation such as encoding or manipulation of numerical information (DeStefano & LeFevre, 2004). The most direct evidence of the involvement of the entire WM system in the arithmetic was drawn from dual-task studies. A simple logic underpinning this experimental paradigm is that a cognitive task (a primary task) is performed by itself and in conjunction with a secondary task, designed to tap a particular subcomponent of working memory. If performance on the primary task significantly decreases when two tasks are performed concurrently, then it is inferred that the WM subcomponent taxed by the secondary task is also involved in the primary task performance. Using this methodology, it was proposed that phonological loop processes (e.g. subvocal rehearsal) are crucial to maintain the accuracy of the digits during multi-digit arithmetic operations such as addition with carry problems (e.g.88+85) in adults (Logie, Gilholly &Wynn, 1994). Phonological loop is used to store partial results in procedural strategies such as counting during carry operation (Hecht, 2002; Fürst & Hitch, 2000) but is not directly involved in the retrieval of simple arithmetic facts (Hecht, 2002). Trbovich and LeFevre (2003) suggested that the extent to which phonological loop resources are utilised in arithmetic might depend on situational constraints such as presentation format of the arithmetic equations. It was shown that horizontal format prompts participants to solve the problems using more multi-step procedures such as counting.

The evidence for the phonological loop involvement in children's arithmetic is drawn from correlational studies. Active dual-tasks and interference paradigms have rarely been used with children to investigate the role of the phonological loop experimentally (Raghubar, Barnes & Hecht, 2010). Nonetheless, McKenzie, Bull and Gray (2003) demonstrated that a passive phonological interference significantly impaired arithmetic performance in 8- and 9- year- olds but had no effect on 6- 7 year olds' performance. It was proposed that this pattern of data might reflect a developmental shift from the use of non-verbal strategies (such as finger counting) to verbal strategies such as retrieval of arithmetic facts. Thus, verbal skills might be more important in older children's arithmetic, whose number representations are firmly established in long-term memory (Siegler, 1999) and accessed primarily by verbal codes (Palmer, 2000). As such, phonological loop supports the retrieval of facts in mental arithmetic tasks and supports the acquisition of new numerical facts in older children, (Holmes & Adams, 2006). However, the relationship between phonological loop and mathematics is not free from complexities and varies also as a function of phonological loop task designed to tap its resources. Bull and Johnston (1997) suggested that word and digit based measures of phonological loop might not reliably differentiate between 7 year old low -and high- maths ability children, once the reading abilities are taken into an account . In a similar vein, Passolunghi and Cornoldi (2008) showed that children with mathematical disability tend to have lower spans only on tasks involving abstract (non-words) and digit-based stimuli. Consistent with these suggestions, a longitudinal study by De Smedt et al., (2009) found that phonological loop measured by non-words emerged as an unique predictor of mathematical attainment in 7-year-olds. In sum, phonological loop tasks might be differentially supported by a retrieval from LTM and this might depend on the verbal content of the phonological task.

Furthermore, the phonological loop contribution to children mathematics is relatively weak. For instance, Holmes and Adams (2006) observed that once the CE had been controlled for, the phonological loop did not contribute to the overall mathematical attainment in 8- and 9- year- olds. Similarly, Swanson and Kim (2007) found that measures of phonological loop accounted for 16% of variance in mathematics in a group of 6 to 10 year old children. However, the scores on phonological loop tasks were significantly correlated with processing tasks reflecting the CE and these measures analysed together had the greatest predictive power in explaining individual differences in mathematics. As a result, it is difficult to elucidate a mechanism by which domain -specific phonological loop resources might support arithmetic fact retrieval and acquisition in children.

Turning to the visuo-spatial working memory (VSWM), the review of adult dual-task literature concluded that the role of VSSP resources in mathematical operations is relatively poorly understood (DeStefano & LeFevre, 2004). Heachcote (1994) suggested that VSSP serves a function of "mental blackboard" on which arithmetic problems are represented in vertical formats. The use of visual imagery might activate a representation of a "mental number line" which allows the application of a strategy similar to when arithmetic is solved using pen-and-pencil. Consequently, Trbovich and LeFevre (2003) showed that VSSP resources might be utilised to a greater extent when adults solve arithmetic problems presented vertically. In line with "mental blackboard" hypothesis, developmental studies have proposed that VSSP resources are implicated in younger school children's arithmetic performance as a result of greater reliance on visuo-spatial coding of information during calculation (McKenzie et al., 2003) and in preschool children who represent and solve arithmetical problems in a concrete, non-linguistic manner (Rasmussen & Bisanz, 2005).On the contrary, older children might use the VSSP under specific conditions. Holmes and Adams (2006) showed that the VSSP measure was an unique predictor of 9- year -olds performance on difficult mathematical problems. It was proposed that older children might use visuo-spatial strategies as "a back-up" to solve complex mathematical problems which are not directly retrievable from LTM (Reuhkala, 2001).

Alternatively, the age-related differences in the extent to which the VSSP resources are implicated in mathematical cognition by younger and older children might reflect developmental changes in the visuo-spatial working memory (VSWM) architecture. The VSSP is comprised of two separable visual and spatial stores (Logie, 1995) and visual and spatial memory follow different developmental trajectories with a rapid development of visual memory and more prolonged development of spatial memory (Logie & Pearson, 1997; Hamilton, Coates & Heffernan, 2003).Using this fractionated model of the VSSP, Holmes, Adams and Hamilton (2008) found that visual and spatial components are differentially related to mathematical attainment in children. Visual memory predicted performance on number, algebra and data handling skills in the 9- to 10- year- olds. On the contrary, the spatial component predicted performance in the 7- to 8 -year- olds on tasks involving spatial manipulation. It was tentatively suggested that performance on VSSP tasks might be scaffolded by the central executive resources. As such, the VSSP tasks might be, in addition to storage, involved in active processing of visuo-spatial codes (e.g. Rudkin, Pearson & Logie, 2007).

An important and consistent finding in the literature is that the central executive plays an important role in almost all types of mathematical cognition (DeStefano & LeFevre, 2004). Aschcraft (1992) argued that the CE is important for simple retrieval of numerical facts from LTM. In general, the evidence from adult dual task literature suggests that the CE processes are implicated in procedural strategies such as counting or transformation (Logie et al., 1994; Hecht, 2002; Seitz & Schumann-Hengstler, 2000, 2002). As such, it has been proposed that the central executive resources are recruited to support the strategy selection, coordination and monitoring of steps in mathematical calculation. Several studies (e.g. Bull, Johnston, & Roy, 1999; Bull & Scerif, 2001; Holmes & Adams, 2006) have found that measures of central executive have been significantly associated with children's mathematical ability, a result that was congruent with those of adult studies. It has been proposed that the central executive might be indispensable for the acquisition of arithmetical strategies (Bull et al., 1999), switching between strategies or retrieval plans (McLean & Hitch, 1999) and inhibition of the use of a well-learned strategy to solve different types or mathematical problems in school-aged children (Bull & Screif, 2001; St Clair – Thompson & Gathercole, 2006). More recently, using an experimental approach, Barrouilett and Lèpine (2005) and Imbo and Vandierendonck (2007) demonstrated more directly that another function of the CE – i.e. direct retrieval from LTM is importantly implicated in children's arithmetic performance. Thus, these studies have suggested that the general resources support wide aspects of arithmetic performance and might be differentially recruited to support strategy selection and execution in arithmetic tasks.

In summary, the empirical evidence suggests that all WM components: are differentially implicated in adult and children's mathematical cognition. The degree to which phonological and visuo-spatial working memory slave systems are involved in mathematics depends on the type of the arithmetic problem under investigation, the age of the problem-solver and the strategy used to tackle mathematical problems. Central executive functions are important for general mathematical cognition at all ages and contribute to the performance on working memory tasks. Overall, both processing and storage elements of WM system are important for the development of mathematical skills (Swanson & Kim, 2007). WM components have been experimentally studied in relation to specific mathematical operations in adults (De Stefano & LeFevre, 2004) but not frequently in children (Holmes & Adams 2006; Holmes et al., 2008). From this basis, the overall aim of this study was to examine the role of the phonological loop and visuo-spatial sketchpad in an on-line 9 and 10 year old children's arithmetic performance using a widely-researched tripartite WM framework (Baddeley & Logie, 1999). A dual-task methodology was employed to achieve this aim. It was hypothesised that active phonological and spatial interference will disrupt performance on a simple arithmetic task. Following Trbovich and LeFevre (2003) results, the study investigated the effects of presentation format on arithmetic performance. It was hypothesised that horizontal presentation might prompt children to use phonological strategies to solve sums and as a result, performance in this condition might be negatively affected by a phonological interference. Conversely, the vertical presentation might result in a greater recruitment of visuo-spatial imagery and thus, the performance on arithmetic presented in this format might suffer from spatial interference. Given the importance of the central executive in arithmetic skills development and WM tasks performance, the current study also examined the central executive contribution to arithmetic and performance on WM tasks

## METHOD

### Design

A mixed 2 x 3 design was used. There was one between-subjects factor (arithmetic task presentation format) with two levels: horizontal and vertical. The within-subjects factor was arithmetic task with three levels: baseline arithmetic, arithmetic with phonological task (phonological load) and arithmetic with VSSP task (visuo-spatial load). Participants' response time (RT) and accuracy scores on arithmetic task at baseline and under the phonological and VSSP load constituted a dependent variable. The order of administration of the visuo-spatial and phonological tasks was counterbalanced to control for presentation effects. To control for trade-off effects, performance on VSSP and phonological tasks under the dual-task conditions was measured to identify the effects of concurrent arithmetic task on working memory in a 2 x 2 repeated measures design. The first within factor was the type of WM task with two levels: visuo-spatial or phonological and a second factor was the amount of cognitive load (with two levels): working memory task at baseline and working memory task with a concurrent arithmetic task. The scores on WM tasks constituted a dependent variable.

### Participants

The participants were pupils of two primary schools in the North-East area of England. A total of 23 year 5 children took part in the study, ten males and thirteen females (age range 9 – 11 years old, mean age = 9.35 years, SD=.65). Parental consent form was obtained for each child who participated in the study (Appendix A). The schools were recruited by letters and emails and voluntarily took part in the study (Appendix B). The children who took part in the study were of varied academic profiles and no children were excluded from the study.

### Materials & Apparatus

#### Apparatus

A computer programme was developed to record participants' RT and accuracy. The addition problems were displayed in the centre of a 17 " laptop screen. (Appendix C – software screen-shots)

#### Materials

#### Arithmetical tasks

The main experimental stimuli consisted of 48 visually presented simple addition problems. 16 sums were generated for each experimental condition. The arithmetic questions were constructed using RT data reported by Groen and Parkman (1972). The equations had two integers: double-digit (from decade 10 through 80 + single digit (no carry, addends included were from 2 to 7). The addition problems were classified as "hard" because solution latencies for each problem were reported to be larger than 3.2s (Groen & Parkman, 1972; Adams & Hitch, 1997). A list of the arithmetic questions used is provided in Appendix D.

**Working Memory Tasks**

The tasks to tax visuo-spatial and phonological memory were constructed from the standardised WM measures from the Working Memory Test Battery for Children (WMTB – C; Pickering & Gathercole, 2001).

***Phonological loop task.*** The Non-word List Recall is reported to be a pure measure of phonological loop functioning. The non-words used in this task contain unfamiliar phonological structures and as a result, the support from LTM is limited (Gathercole, Willis, Baddeley & Emslie, 1994). The experimenter orally presents the non-words at the rate of 1 per second. The task requires a child to immediately recall a spoken sequence of nonsense words in the same order as presented by the experimenter. Mean test–retest reliability coefficient for this measure is .56. (Gathercole et al., 2004). A list of 16 sequences is provided in Appendix E.
***Visuo-spatial - sketchpad task.*** The Block Recall (Pickering & Gathercole, 2001) is considered to be a measure of spatial component of the VSSP (Logie, 1995).The stimuli consists of a plastic board with nine blocks arranged in a random order. The experimenter taps a block (or a sequence of blocks) and the child's task is to repeat the tapping in the same order as shown by the experimenter. The mean test–retest reliability coefficient for this measure is .53. (Gathercole et al., 2004). A list of 16 sequences is provided in Appendix F.

**Procedure**

The experimental procedure was granted an ethical approval by the Undergraduate Ethics Committee (Appendix G). The participants were randomly allocated to either vertical or horizontal arithmetic presentation condition. The children were tested in a quiet school environment (library/teacher's room). Testing session commenced with a practice of an arithmetic task (full experimental instructions-Appendix H). Children were allowed 5 practice trials were allowed to familiarise with computer programme. Once the participant was ready, the baseline arithmetic condition was administered. The presentation of arithmetic problems on a computer was self-paced. After a successful completion of 16 arithmetic baseline trials, the participants were given a 5 minutes' break. Next, children were presented with working memory tasks at baseline. Phonological loop task was introduced as "mysterious words" stage of the game. The participants were required to recall a list of three one-syllable non-words over the course of 16 trials and were allowed 2 trials practice beforehand. The length of the non-word list was fixed for each trial and determined using the standardised spans data for children aged 9 – 11 years (Pickering & Gathercole, 2001). A point was awarded for each correct trial; all three words had to be recalled in a correct order for the trial to be scored as "correct". The VSSP task was introduced to the children as "Let's play with the blocks" stage of the game. The number of trials and the length of sequence (3 blocks) and scoring procedures were analogical to phonological loop task. Dual-task condition (arithmetic + WM tasks) commenced after a short 10 minute break

In dual task condition children were required to recall 3 non-words/blocks immediately (in phonological and visuo-spatial load, respectively,) then solve a sum on a computer, recall the non-words/blocks after the completion of the arithmetic task and learn a new sequence of non-words/blocks for immediate recall. The block-recall board was out of view during arithmetic task. This continued until 16 trials were completed and breaks were given (length determined on an individual basis) between the two dual-tasks for each participant to minimise the carry-over effects. Upon the completion of the study, the children were thanked and given a participant debrief form for the parents (Appendix I). Finally, project feedback sheets (Appendix J) were sent to schools and parents.

## RESULTS

### 1. Impairment of Arithmetic Task Performance by the Secondary WM Task

The first part of the analysis compared arithmetic performance data (accuracy and RT) under the three experimental conditions (addition task – baseline, addition with concurrent phonological task and addition task with concurrent visuo-spatial task). A 3x2 Multivariate ANOVA was conducted to verify the hypothesis that WM load will result in decrements on addition task performance (Appendix K for SPSS outputs). The effect of presentation format (horizontal and vertical; between-subjects factor) was also examined. The overall results are presented in table 1 and 2. (Raw accuracy and RT scores in appendix L)

**Table 1**

**Means and standard deviations on the arithmetic task accuracy as a function of presentation format and cognitive load (N=23)**

| | | **Cognitive load** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **Baseline** | | **Phonological Load** | | **VSSP load** | | **Overall** |
| | | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* |
| **Presentation Format** | **Horizontal** | 15.58 | .79 | 14.91 | 1.44 | 14.83 | 2.37 | 15.10 |
| | **Vertical** | 15.45 | 1.21 | 14.90 | 1.30 | 15 | 1.34 | 15.11 |
| | **Overall** | 15.45 | | 14.90 | | 15 | | 15.11 |

**Table 2**

**Means and standard deviations on the arithmetic task reaction times (RT) as a function of presentation format and cognitive load (N=23)**

| | | Cognitive load | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **Baseline** | | **Phonological Load** | | **VSSP load** | | **Overall** |
| | | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* |
| **Presentation Format** | **Horizontal** | 8.10 | 2 | 8.58 | 2.46 | 9.52 3.24 | | 8.73 |
| | **Vertical** | 7.58 | 2.74 | 7.80 | 2.71 | 8.04 3.23 | | 7.81 |
| | **Overall** | 7.84 | | 8.20 | | 8.81 | | 8.27 |

## 1.1 Mean accuracy scores analysis

The accuracy data met the sphericity assumption; Mauchly's W = .891, $\chi^2(2) = 2.30$, *p*=.317. A multivariate analysis revealed no significant main effect of memory load on the participants' accuracy scores on arithmetic task: Wilks's Lambda= .874, $F(2,20)=1.443$, *p*=.206. This implied that participants' accuracy scores did not change as a result of secondary task distraction and this is confirmed by the means displayed in the table 1. The presentation format of the arithmetic task did not affect the accuracy scores; $F(1,21)=.001$, *p*=.979 which did not significantly differ for the two formats (table 1) Consequently, these findings were qualified by a non-significant interaction effect between concurrent WM loads and presentation format factors: Wilk's lambda=.996, $F(2,20)=.044$, *p*= .957.

## 1.2 Mean correct RT analysis

Mean RT on correct trials in each condition were calculated. The RT data met the sphericity assumption; Mauchly's W = .776, $\chi^2(2) = 5.08$, *p*=.079. Multivariate analysis revealed that there was no significant main effect of memory load on the participants' RT: Wilks's Lambda= .767, $F(2,20)=3.03$, *p*=.071. The result indicated that the secondary task did not significantly affect children' RT on arithmetic task and the means presented in table 1 -(section RT) reflected this . The between-factor manipulation (presentation format) had no effect on arithmetic solution RT: $F(1,21)=.753$, *p*=.395. RT's for sums presented horizontally did not differ significantly from RT's in vertical presentation (table1, section RT). These findings were qualified by a non-significant interaction between concurrent WM loads and presentation format factors: Wilks's Lambda: =.931, $F(2,20)=.745$, *p*=.487.

**2. Performance on secondary tasks (non-words recall and block recall)**

It was hypothesised that the performance on arithmetic task might have been protected against the performance on the secondary WM tasks. The mean scores and standard deviations of correctly completed working memory across the two experimental conditions are displayed in table 3. (Raw WM scores-Appendix M)

**Table 3**

**Mean accuracy scores and standard deviations on working memory tasks in single and dual task conditions (N=23)**

| | | **WM Task** | | | | |
|---|---|---|---|---|---|---|
| | | **Non-words** | | **Block recall** | | **Overall** |
| | | *M* | *SD* | *M* | *SD* | *M* |
| **Experimental condition** | **Single (baseline)** | 14.70 | 1.33 | 15.17 | 1.19 | 14.93 |
| | **Dual (with arithmetic)** | 12.22 | 2.78 | 7.48 | 2 | 9.85 |
| | **Overall** | 13.46 | | 11.33 | | 12.43 |

The analysis of working memory mean scores (table 3) performed by 2 x 2 repeated measures ANOVA (Appendix N for SPPS output) yielded a significant main effect of experimental condition on the accuracy on working memory tasks, Wilks's Lambda=.082, $F(1,22)=245.54$, $p<.001$, with significantly higher scores on baseline working memory tasks ($M$ non-words$_{\text{+block recall (baseline)}}$ = 14.94) than on working memory tasks performed in conjunction with arithmetic ($_{\text{M non-words+block recall (dual-task)}}$ =9.85), $\eta^2=.918$.

There was a significant main effect of the type working memory task on the recall scores, Wilks's Lambda=.506, $F(1,22)=21.44$, $p<.001$, with significantly higher overall recall scores on non-word recall task ($M_{\text{non-words}}=13.46$) than on block recall- task ($M_{\text{block recall}}=11.33$), $\eta^2=.494$ The main effects of the amount of cognitive load in each experimental condition and the type WM task were qualified by a significant interaction effect : Wilks's Lambda=.203, $F(1,22)=86.134$, $p<.001$,$\eta^2=.797$. This interaction effect indicated that the difference in mean scores between non-word recall and block recall depended on the amount of cognitive load (Figure 1).

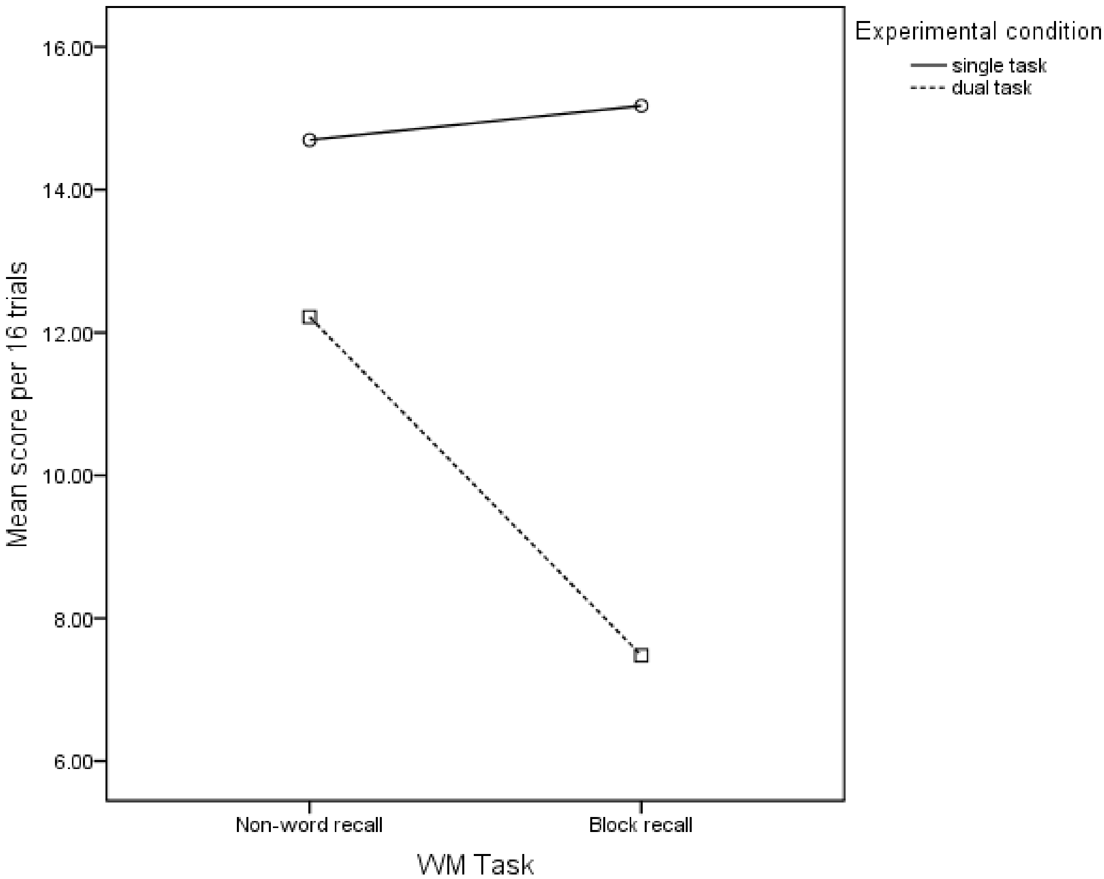


**Figure 1: Plots illustrating the interaction effect of the type of working memory task and the type of experimental condition on recall scores (N=23)**

The interaction effect illustrated by Figure 1 showed that the difference in mean recall scores between non-words task and block recall is only significant under dual task condition (with arithmetic) with higher scores on non-words recall task ($M_{\text{non-words dual-task}}$ =12.22) than on block recall task ($M_{\text{block recall dual-task}}$ =7.48). The difference in scores between these two tasks was non- significant under single -task with participants performing at a similar level on non-word recall ($M_{\text{non-words baseline}}$ =14.70) and block recall task ($M_{\text{block recall baseline}}$ =15.17).

## 2.1 Secondary Task impairment – Central Executive Contribution

It was hypothesised that a negative effect of arithmetic task on block recall and non-word recall accuracy might reflect the contribution of the central executive. An index of the ability to coordinate concurrent arithmetical task with working memory task in the dual task condition (*mu;* Baddeley, Della Salla, Papagano & Spinnler, 1997) was calculated for each participant (Appendix O). Mean *mu* values were analysed by a paired samples t-test (Appendix P, SPPS output). There was a significant difference between the mean *mu* values; $t$ (1, 22) = 5.219, $p$ <.001. The ability to coordinate arithmetic with concurrent phonological loop task was greater ($M_{\text{Mu value non-words recall}}$= 90.08, SD=9.63) than ability to combine arithmetic task with VSSP task ($M_{\text{Mu value block}}$

$_{recall}$ = 74.35, SD=10.59).

**Summary**

The results showed that the overall arithmetic performance (measured by accuracy and RT) was not affected by the concurrent working memory load. Furthermore, the level of working memory involvement in arithmetic did not depend upon the factor of presentation format. On the contrary, the arithmetic task exerted a significant effect upon performance on the WM tasks. Both phonological loop and VSSP tasks were significantly impaired in dual-task condition as compared to baseline, although the effect was more pronounced for the Block Recall task. Further analysis of the effects of arithmetic on WM tasks performance indicated that the ability to perform an arithmetic task with concurrent VSSP task was significantly lower than the ability to solve arithmetic sums with phonological loop task

## DISCUSSION

This study explored the involvement of working memory in children's arithmetic, with a focus on the role of verbal and non-verbal working memory (WM) processes in children's simple arithmetic performance. It was expected that phonological and visuo-spatial interference might disrupt strategy efficiency in simple addition but the degree of interference might vary as a function of arithmetic task presentation format. The first main finding of the study revealed that phonological and visuo-spatial sketchpad tasks (VSSP) did not impair overall performance on arithmetic task. The lack of WM interference on arithmetic performance suggested that there was a minimal role of verbal and visuo-spatial working memory in arithmetic. This is not entirely consistent with previous studies which used a similar methodology with children (McKenzie et al., 2003) and with correlational data (e.g. De Smedt et al., 2009). There are methodological differences between these studies and the current experiment which may account for this: the maths task and the dual-task paradigm.

The arithmetic task was developed using a chronometric analysis table (Groen & Parkman, 1972) which was based on average solution times to complete the min counting procedure in simple addition by 6 year olds. Given the age of children in the present study and the nature of the arithmetic task (simple addition problems with non-carry, e.g. 44+3), it can be argued that children could have predominantly used direct memory retrieval to solve these problems. This strategy is frequently used by typically developing 9-10 year old children who receive a lot of practice in arithmetic through schooling (Bull & Johnston, 1997; Geary, Hoard, Bryn-Craven & DeSoto, 2004). Further support for this suggestion comes from an experimental study by Imbo and Vandierendonck (2008) which showed that 10-year olds used retrieval 88% of times across on simple problems (total sums smaller than 25) involving carry-problems (e.g. 8+7). In addition, the retrieval strategy was characterised by high rates of accuracy – 98%. Similar results were obtained in a dual task in which the accuracy rates for simple addition problems performed by 10- and 12- year- olds under central executive (CE) load were close to 100% (Imbo & Vandierendonck, 2007).

On the basis of these observations, the non-significant effects of phonological load on arithmetic strategy efficiency appear to be in line with the suggestions that phonological loop is used to support storage of interim results in difficult arithmetic problems when procedural strategies are used (Logie et al., 1994). Similar conclusions can be drawn from developmental studies. McKenzie et al. (2003) found the effects of the passive phonological interference on accuracy scores when children were faced with more difficult three-digit mathematical problems involving subtraction. The interference did not affect the solution RT in a sample of school-children. Conversely, Holmes and Adams (2006) showed that non-word recall uniquely predicted mental arithmetic performance in children aged 9 years on curriculum-based mental arithmetic tasks, which probably involved a range of operations involving multiplication and carry-based addition. Other studies which found unique contribution of phonological loop skills to mathematical attainment assessed general mathematical skills (e.g. De Smedt et al., 2009). As such, the present findings may tentatively reflect an interaction between the type of arithmetic problem and the degree of phonological memory involvement which may vary as a function of a strategy used by the problem solver.

This suggestion can be further supported by the adult dual- task studies which have shown that phonological loop involvement is maximal when counting procedures are used to support performance on complex problems such as multi-digit carry operations (Fürst & Hitch, 2000) but minimal when automatic strategies such as direct retrieval are implemented (Hecht, 2002). Certainly, as children are flexible strategy users (Siegler, 1999) the argument would be stronger if arithmetic strategy had been directly controlled for in the present study. This can be done by the means of a verbal report (Siegler & Crowley, 1991) or choice/no choice paradigm in which participants are directly instructed to solve a problem using a specific strategy, e.g. counting (Lemaire & Callies, 2009; Siegler & Lemaire, 1997). Given the high probability of retrieval use on arithmetic task, the finding that the VSSP did not affect the arithmetic performance is consistent with the developmental literature reviewed in the Introduction. It was proposed previously that visual imagery strategies are used by children aged 9 – 10 only on difficult problems as a “back up” (Holmes & Adams, 2006; Holmes et al., 2008). Children typically do not use visual strategies to solve simple arithmetic problems because the translation of verbal codes into visual images (“recoding strategy”) is relatively attentionally demanding (Pickering, 2001). Similarly, visual imagery is not used spontaneously by adults to solve simple arithmetic problems, easily retrievable from LTM (Logie et al., 1994).

Contrary to the expectations, the involvement of the slave systems did not vary as a function of presentation format and this inconsistent with the initial hypothesis drawn from Trbovich and Lefevre (2003) study. Methodological differences could partially explain this pattern of data. First, the former study investigated performance on more difficult problems (with carry) in adults. Not much is known about presentation format effects on children's strategy use and working memory recruitment. More recently, Lemaire and Callies (2009) showed that complex arithmetic (with carry problems) presented in horizontal and vertical problems is solved by strategies involving different number of steps (e.g. full or partial decomposition) by adults and school-children. Perhaps presentation formats could affect performance on simple arithmetic in preschoolers whose strategic repertoire is less flexible and driven by perceptual cues (Siegler, 1999). Secondly, presentation format was a between-groups factor in the current study. This could have decreased the chance of detecting presentation effects due to a low power. In addition, the former study employed a visual task to tax the VSSP. Thus, it could be that the spatial memory task used in the present study tapped different processes which were less central to the direct visualisation of sums. Last of all, the presentation format might have been less relevant to children's strategies, given that the sums were visible to children during problem solving. This could have significantly reduced working memory load in the arithmetic tasks. Adams and Hitch (1997) suggested that visual presentation of simple arithmetic problems resulted in higher addition spans in school-aged children. As such presentation format might have a greater relevance to an occasional visual strategy use in multi-digit mental arithmetic when no visual aids are provided.

Turning to the performance on the secondary task, the analysis revealed that performance on arithmetic was protected against non-word and block recall. This finding was highly significant and necessitates a further explanation. The first account which could be compatible with the finding is a strategic trade-off factor (Navon & Gopher, 1979). According to this theory, if the primary task is less demanding (e.g. arithmetic task) than a secondary memory task, then participants might allocate more effort and resources to the secondary task to protect the performance on a primary, less demanding task. This account would predict decrements on the simple addition solved by an automatic direct retrieval, if the resources were allocated to working memory task. It appears however, that the resources were allocated to arithmetic and as such, the performance on working memory tasks in dual-task condition has suffered from impairments.

There are multiple reasons for this pattern of resource allocation, depending on the theoretical perspective to WM. First, in terms of functional architecture of the working memory system, this strategic-trade off might reflect that both arithmetic and WM tasks relied on a general, processing resource. Given the non-unitary nature of the CE, which is responsible for retrieval of facts from temporarily activated LTM, inhibition and task switching (Baddeley, 1996; Baddeley, 2007), it can be argued that regardless of what strategy was used to solve the sums, the CE resources were implicated in the calculation process. The evidence reviewed in the Introduction supports this suggestion: the CE resources are implicated in procedural, multi-step strategies (De Stefano & LeFevre, 2004) and direct retrieval of arithmetic facts (Aschcraft, 1992; Imbo & Vandierendonck, 2008).In this manner, the observed-trade off might suggest that similar cognitive mechanisms underpinned the performance on working memory and arithmetic task. As such, it can be argued that it was not the simple “difficulty” of the spatial and verbal tasks but rather their nature that resulted in significant decrements in recall accuracy in dual-task condition. This is supported by the baseline data which showed that all children performed to very high standards on both working memory tasks. However, the analysis of performance on block and non-word recall revealed that these tasks placed a differential demands on the CE in the experimental context. The *mu*-values which are a measure of the main attentional controller – the CE – indicated that the ability to coordinate performance on dual task was significantly lower for spatial task and opposed to phonological task.

A significant drop in performance on spatial task in the face of distraction of an arithmetic task could be explained on the theoretical grounds by specific models of visual working memory (VSWM) proposed by Logie (1995) and Pearson (2001). In Logie's (1995) model spatial component (the inner scribe) is involved in an active spatial rehearsal of a material maintained temporarily in a visual store and this process is supported by the activity of the CE. Further, Pearson (2001) made explicit presumptions that the CE is involved in the production and maintenance of conscious mental images derived from perception or LTM. Given the assumptions of these models, it can be argued that the spatial task used in the present study might have additionally tapped a proportion of different processing resources. An experimental study by Rudkin, Pearson and Logie (2007) suggested that block recall task involves encoding and maintenance of sequential information and this process is attentionally taxing in adults (experiments 2 and 3). Hamilton et al., (2003) tentatively suggested that the central executive resources might underpin the development of spatial memory which continues into early adulthood (Study 1). A subsequent investigation showed that different interference formats (tapping the CE or phonological loop) had a detrimental effect on the spatial span task in children (Study 2). From this vantage it can be argued that spatial task used in the current study involved attentional and executive control. Some research has suggested that maintenance and rehearsal of spatial information involves central executive resources because the application of automatic heuristic strategies (such as rules of symmetry) is difficult with dynamic spatial content (Kemps, 2001). These strategies might directly support encoding, maintenance and immediate retrieval of sequences and thus make the task less “taxing”. Anecdotal evidence from the current study suggested that some children applied such heuristics and this helped them to encode and retrieve a sequence (e.g. children noted that some sequences resembled a triangle). From this basis, it is plausible that the executive arithmetic task might have interfered at some point with encoding, maintenance or strategic rehearsal of sequential information.

The impairments on non-word recall in dual-task were lower in comparison to block recall. This could be a result of the type of the non-words that were used which were relatively short and some resembled English words, (e.g. "pab”,"terch" or "bock") and it could be that it was relatively easier for children to maintain this type of stimulus in working memory. Although non-word recall is thought to be minimally supported by the long-term knowledge (Bull & Johnston, 1997; Passolunghi & Cornoldi, 2008), the existing linguistic long-term knowledge might support encoding and recall of a non-word that approximates an English word (Gathercole, 1995). It might be possible that this process is relatively automatic in 9-10- year old children. Finally, it can be argued that children's performance on phonological loop was more stable in comparison to block recall because the verbal task was more passive, i.e. did not involve a significant amount of manipulation of the material, just a temporary storage and relatively non-taxing rehearsal. On the contrary, block recall involved an execution of a few responses, including motor execution, visual scanning (Hamilton et al., 2003) and selective orienteering of attention (Awh & Jonides, 2001).

These explanations are in line with a new Baddeley (2007) model which suggests that whereas rehearsal within the visuo-spatial system involves paying continued attention to the material being rehearsed, maintaining material using the phonological loop is much less attention-demanding. This explanation is valid if one accepts that the current dual-task is a valid measure of the CE which reflects an ability to divide attention. It must be noted that the CE is a non-unitary and responsible for other functions such as retrieval of information and there is lack of theoretical agreement on the nature of the CE (Andrade, 2001). In addition, there are some objections to the validity of the *mu* value in clinical use (Baddeley et al., 1997). In support, Bull and Scerif (2001) showed that dual -task performance measured by *mu* was not related to children's mathematical ability, but other measures relying on similar processes (task, switching, and inhibition) were.

Alternatively, the trade-off effects might be tentatively explained by more unitary models of WM which suggest that attention is shared between processing (CE) and storage (e.g. Engle et al., 1999). According to Barrouilett and Camos (2004) attention is required to complete any type of cognitive task, as both processing and maintenance rely on attentional resources. When tasks are combined together, attention is switched away from tasks involving maintenance of items (e.g. blocks and non-words) and focused on processing task (e.g. on retrieval of arithmetic facts from temporarily activated long-term memory). Consequently, items held in working memory (blocks and non-words) suffer from a time-related decay. In order to refresh to-be-recalled items, participants had to actively retrieve them from working memory. The arithmetic task might have occupied the retrieval processes and the performance on working memory was constrained as, according to this model, only one retrieval can be completed at a time.

The discussed trade-off effects in the current study suggest that the employment of dual-task paradigm with children in order to study processes in working memory is theoretically and practically problematic. Any processes involved in arithmetic or working memory might be obscured by the differences between adults' and children's ability to direct and divide attention between the two tasks. It has been shown previously that the ability to control attention according to one's goals and intentions changes with age (Karatekin, 2004). As such, in order to apply dual-task logic tasks taxing slave systems need to be more pure and relatively and free from “executive scaffolding”. Furthermore, factors affecting children's management of attention such as task priority (determined by instructions or varying time intervals between tasks) need to be controlled experimentally (Irwin-Chase & Burns, 2000).

In summary, the current study provided evidence that working memory resources are differentially implicated in children's arithmetic but the degree of WM recruitment measured by dual-task might depend on the attentional resources allocation which might have an impact on strategic behaviour. Significant trade-off effects could reflect a competition for general processing resources (the CE) between simple addition and verbal and visuo-spatial tasks. As such, WM was to some extent involved in children's arithmetic because phonological loop and VSSP systems required attentional resources (perhaps used to support the retrieval of information), which were shared with calculation processes in arithmetic. The main implication of the study is that in order to detect the VSSP and phonological loop involvement in arithmetic experimentally, it is first crucial to identify the processes on which WM tasks rely. Future studies might be more informative if dual-task paradigms are combined with individual differences approach to determine which factors (WM span, strategy use, arithmetic skill, speed, top- down/bottom up- attention) contribute to the strategic development in different types and formats of arithmetic.

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