THE CONTRIBUTION OF VISUAL PROCESSING SPEED TO VISUAL AND AUDITORY WORKING MEMORY IN EARLY SCHOOL YEARS

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Abstract - Although brain imaging indicates that the visually driven parieto-frontal network is the predominant neural network underlying working memory (WM) and aspects of visually driven working memory are apparent in early infancy before children develop verbal language, it remains unclear how the visual and auditory sensory systems contribute to WM development during early school years. Thus, the current study aimed to examine age-related changes in WM in children (n=100, 5 -7 years) employing visual and auditory verbal Digit Span tasks as the dependent variable measures and structural equation models to determine the predictive contribution of aspects of visual processing speed to WM. Cognitive processing speed was measured utilizing a simple visual inspection time (IT) task, a visual-verbal processing task (Rapid Automatic Naming (RAN) of objects), and a visuo-motor game-like iPad application, (the 'SLURP' task). The key finding of this study was that both visual and auditory WM span improved significantly with age, though these children all showed better performance on auditory than visual WM tasks. Our results also showed that age related increases in speed of visual information processing contribute strongly to visual but not auditory WM development. Results of the current study are consistent with the notion that visual and auditory WM are dissociable cognitive domains that develop at differential rates as the child learns to read.

Keywords - Processing Speed, Sensory Processing, Children, Working Memory, Short-Term Memory, Visual Working Memory, Auditory Working Memory, Visuomotor Performance, Time Estimation

I. INTRODUCTION

A growing body of literature suggests that rate of information processing speed especially visual processing (A. Fry & Hale, 2000; Tuch et al., 2005), leads to individual differences in the foundational and essential cognitive functions such as working memory (Coyle, Pillow, Snyder, & Kochunov, 2011; Fry & Hale, 1996; A. Fry & Hale, 2000; Kail, 2000; Salthouse, 1992). Based on a neuroanatomical perspective, brain-imaging studies have reinforced that speed of information processing assessed visually (Tuch et al., 2005) and working memory share standard neuroanatomical networks such as parietal and prefrontal cortex(Awh & Jonides, 2001; Awh, Vogel, & Oh, 2006; Chun, 2011; Gazzaley & Nobre, 2012; Takeuchi et al., 2011). As suggested by Tuch et al. (2005) and Klingberg (2006), visual processing speed is associated with white matter maturation which in turn contributes to WM development. Additionally, a wide range of behavioural studies investigating the relationships between information processing speed and WM were based on visual processing tasks rather than auditory tasks especially semantic tasks as the time top pronounce a word or syllable (Anderson & Wagovich, 2010; Chen & Li, 2007; A. R. A. Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Dang, Braeken, Colom, Ferrer, & Liu, 2015; Kail, 2007; Nettelbeck & Burns, 2010; Pickering, 2001; Tourva & Spanoudis, 2020; Tourva, Spanoudis, & Demetriou, 2016). Hence, we set out to look at whether visual or auditory working memory performance is superior at particular ages and whether age related changes in visual processing measures can contribute equally to visual and auditory WM (Anderson & Wagovich, 2010; Chen & Li, 2007; A. R. A. Conway et al., 2002; Dang et al., 2015; Kail, 2007; Nettelbeck & Burns, 2010; Pickering, 2001; Tourva & Spanoudis, 2020; Tourva et al., 2016).

Working memory is recognized as a complex function essential to performance on all the simplest of cognitive functions (Baddeley & Logie, 1999)and usually defined as the ability to retain, process and manipulate more than one bit of sensory information simultaneously(Dang et al., 2015; Demetriou, Spanoudis, & Shayer, 2013; Demetriou et al., 2014; Gray et al., 2017; R. V. Kail, 2013).Working memory relies on speed of visual information processing development, since the development of processing speed enhances WM capacity (Kail, 2007; Tourva & Spanoudis, 2020; Tourva et al., 2016).

Theoretically, working memory is thought to rely on multiple-domain specific systems (Baddeley & Hitch, 2000; Baddeley & Logie, 1999) or a single-domain attentional system (Cowan, Nugent, Elliott, Ponomarev, & Saults, 1999). According to Baddeley's multi-components model, WM comprises a domain-general process that is associated with attention (central executive) and two slave storages the phonological loop (dealing with auditory and verbal information) and visuospatial sketchpad (for visual and spatial information) (Baddeley & Hitch, 2000; Baddeley & Logie, 1999). However, the domain-general component of WM suggested by Cowan et al. (1999) includes a focus of attention that retains visual information for further processing, and central executive that is involved in retaining this

information in an active state that can be transferred to the long term memory. Notably, the use of focus of attention decreases in older children (+7 years) and adults as they utilize several mnemonic strategies and phonological rehearsals (Cowan et al., 2005; Gray et al., 2017). Many investigators have attempted to compare these two WM components that suggested by Baddeley and Cowan in children. Hornung, Brunner, Reuter, and Martin (2011) have evaluated six different WM components, including Baddeley and Cowan's WM structure using structural equation models in young children 5 to 7 years old. The findings indicate that Cowan's single component of WM seems to have a better fit than Baddeley's multi-components. More recently, Gray et al. (2017) have tested the best WM structure in children aged 7 to 9 years old, and their results were in agreement with Hornung et al. (2011), where Cowan's model provides an excellent fit compare to Baddeley's.

Currently, little is known about the development of WM regarding the task conditions visual or oral stimuli driven. Previous work in examining WM development has either focused on the several components model (short term storage and processing) or the general domain model of WM using a combination of visual and auditory verbal WM tasks within the same experiment. For example, the short term storage component of WM mostly assessed via reading, listening, word, letter, and forward digit spans (visually or aurally stimuli) (Gray et al., 2017; Kail & Hall, 2001; Tourva & Spanoudis, 2020; Tourva et al., 2016), the central processing of WM mainly measured by a reading recognition task, Computation Span, backward digit span (Gray et al., 2017; Kail & Hall, 2001; Tourva & Spanoudis, 2020). Noteworthy, all these measures require verbal recalling, and none of these studies have distinguished the visual WM from auditory components of WM regardless of the nature of information provided to be retained in WM. Despite the fact provided from brain imaging studies suggesting distinct brain region activations during each WM condition (visual and auditory) (Basso, Spinnler, Vallar, & Zanobio, 1982; Chee, O'Craven, Bergida, Rosen, & Savoy, 1999; Crottaz-Herbette, Anagnoson, & Menon, 2004; Klingberg, 1998). Hence, this study firstly aimed to investigate the development of visual and auditory verbal WM in young children.

As alluded to above, speed of information processing is strongly related to WM capacity, with WM having different perspectives and multiple components in both theories. However, it is unknown to what extent processing speed contributes to working memory in young children 5 to 7 years old. Kail and Hall (2001) have conducted two studies evaluating the effect of visual processing speed on working memory as distinct constructs in 8 to 12 year children, short term memory (STM) measured by digit, word and letter spans (all auditory) and WM using reading, listening and least number span (two of them visual). The results of structural equation models of the two studies were inconsistent, PS contributes equally to both constructs (STM and WM) in the first study, however, in the second study PS has a significant effect only on the WM component which tested mostly with visual tasks.

Due to the inconsistently, the current study attempted to compare Kail's model, which assesses the contribution of PS on multi-components of WM (STM and WM), and the effect of PS on WM as a single domain attentional system (visual and auditory), which proposed to be the best structure of WM in young children (Gray et al., 2017; Hornung et al., 2011). Assessing visual and auditory verbal WM would provide insights into the age-related changes in each of them separately and estimated the contribution of PS clearly on each aspect of WM.

II. DETAILS EXPERIMENTAL

Materials

2.1. Inspection Time (IT)

It is a simple computerized task that measures the minimum time required to identify one of three simple stimuli flashing on the screen (Fish, Truck, or Butterfly) using a PEST (parametric estimation of statistical threshold) routine. This task has been modified by (A. C. Brown & Crewther, 2017 ;see Figure 1)

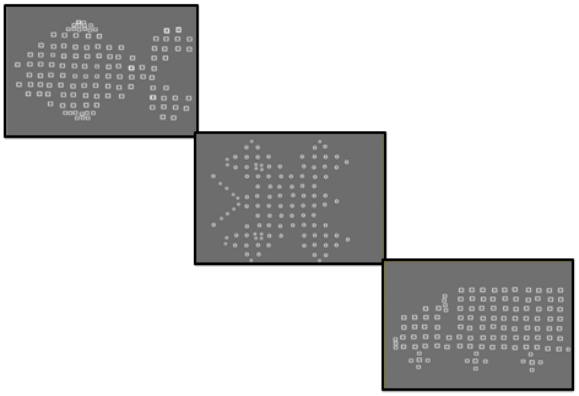

Figure 1: Inspection Time Objects

2.2 Visual verbalization of familiar objects as a measure of speed of information processing

Rapid Automatized Naming (Denckla & Rudel, 1974) was chosen to measure how fast and accurately a participant could verbally name the 36 familiar objects shown on one sheet and hence can be used as a measure of rate of visual-verbal processing. The task starts with a practice trial that consists of all objects (boat, star, pencil, chair, fish, and key), to ensure that each participant is familiar with all objects and consensus name. Then participants were instructed to sequentially name from left to right, as fast as they could, the series of 9 objects in each of the four rows.

2.3 Rate of visuomotor processing using the SLURP task:

To test the development of visuo-motor rate of information processing the Lee-Ryan Eye-Hand Coordination Test (SLURP) was included in our battery. SLURP is an iPad application developed by Kiseok Robin Lee and designed by Malcolm Ryan to assess eye-hand coordination across childhood and adulthood (Lee, Junghans, Ryan, Khuu, & Suttle, 2014). The task requires children to trace shapes with their fingers rapidly and accurately, as the time and errors were recorded. (see **Figure 2**).



Figure 2. **Example of Rabbit trace one of the shapes provided in the SLURP**

2.4*Visual Digit Span Task* A computer task assesses two components of working memory, short-term storage (forward) and additional processing (backward) (A. R. Conway, Kane, & Engle, 2003). Participants are required to repeat visually presented numbers in PC screen, in either forward or backward order. The task discontinues after two consecutive errors within the same span length.

2.5 Auditory Digit Span Task in the auditory modality, participants were instructed to repeat a list of auditorily administered numbers (forward and backward). The test starts first with the forward then the backward condition. The task begins with two digits and the child required to recall them correctly, and the span increases with two trails for each length until two consecutiveerrors.

III. RESULTS AND DISCUSSION

3.1Age differences on WM (visual andauditory)

ANOVA test results demonstrated age related differences between group means in measures of WM spans assessed by visual digit (forward), visual digit (backward), auditory digit (forward) and auditory digit (backward); F (2.93) = 11.191, $p <$ .000, F (2.91) = 3.713, p < .028, F (2.96) = 13.894, $p <$ .000 and F (2.96) = 9.945, $p <$ .000, respectively. Scheffe post hoc analysis indicated that the 7 years group performed significantly from the 5- and 6-year groups in all measures of WM capacity. Furthermore, the 6-year group was significantly different from the 5-year group in the two auditory digit tasks (forward and backward) See **Figure 3**.

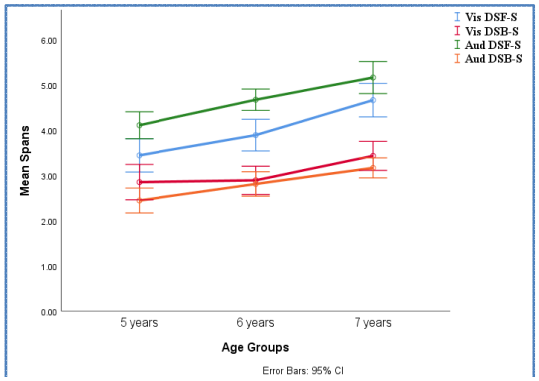

Figure 3.Group differences for visual and auditory Working Memory

Our results provide evidence that performance on the auditory verbal WM tasks that stored in the phonological loop is outperformed visual WM tasks among all three groups (5,6 and 7 years). This result is in agreement with Crowder (1978) who investigated the modality differences of oral and visual WM in young adults and suggested a greater performance on auditory versus visual tasks. However, contrary to wide range of studies suggesting that phonological recoding for spoken information do not improve in children younger than 8 years and only older children are able to use phonological codes to store visual and auditory WM tasks (Baddeley & Hitch, 2000; Baddeley & Logie, 1999; Hitch, Woodin, & Baker, 1989; Pickering, 2001). Accordingly, younger children (under 8 years) relay more on visual WM when recalling visual stimuli, and at 8 years they use both visual and phonological decoding to recall visual and auditory objects (Baddeley & Hitch, 2000; Baddeley & Logie, 1999; Cowan et al., 2005; Pickering, 2001). However, it has been confounding in the literature when assessing visual WM with digit span tasks that children younger than 7 years of age might be able to count verbally but are not familiar with the numbers visually. Consequently, their performance on auditory would be better than visual digit spans since children under 7 years of age cannot read easily which in fact limit their ability to do visual digit span tasks. Hence, the outperformance on the auditory tasks in our study is that, children from 7 years are more likely able to read and write which in turn encourage their phonological rehearsal and developing more mnemonic strategies leading to phonologically decoding improvement (Anderson & Wagovich, 2010; Ang & Lee, 2010; Conant et al., 2003; Pickering, 2001).

3.2 The contribution of processing speed to working memory

Two structural equation models were conducted to determine to what extent speed of information processing predicts working memory as presented in **Figure 4** and **5**. The first model (**M1**) was a replication of Kail and Hall (2001) model as they divided WM into two components STM (retaining

information for short time) and WM (additional processing). The path coefficients from age to PS, STM and WM reached a significance level (β -.61, .39 and .40) respectively, neither the paths from PS to STM nor WM were significant (β -.38 and -.25) respectively, see **Figure 4**. **Table 1** exhibited the fit statistics for **M1**, which provided a good fit as evaluated with RMSEA (.07).

Nevertheless, when the nature of information (visual and auditory) and a single domain of WM (Cowan et al., 1999) were considered in the second model **M2**, RMSEA presented an excellent value (.000) which was much better than **M1**, see **Table 1**. The second model (**M2**) consisted four factors as well, chronological age, PS, visual working memory (VWM, visual forward/backward digits) and auditory working memory (AWM, auditory forward/backward digits). The path coefficients from age to PS and AWM was statistically significant (β .60 for both); however, the path from age to VWM was not. In contrast, PS significantly contributed to VWM (β -.62), but the path from PS to AWM did not reach a significance level (β -.11); see **Figure 5**.

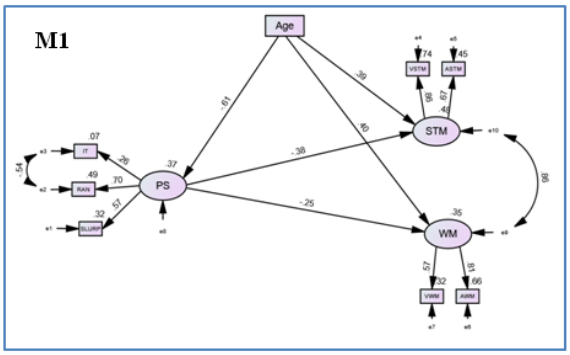

Figure 4: Diagrams of model 1 (M1). PS, processing speed; IT, Inspection Time (visual processing); RAN, Rapid Automatized Naming visual object verbalization (visual-verbal processing); SLURP, total duration in seconds (visual-motor processing) STM, short term memory (storage); VSTM, visual forward digit; ASTM, auditory forward digit span; WM, working memory (processing); VWM, visual backward digit; AWM, auditory backward digit span

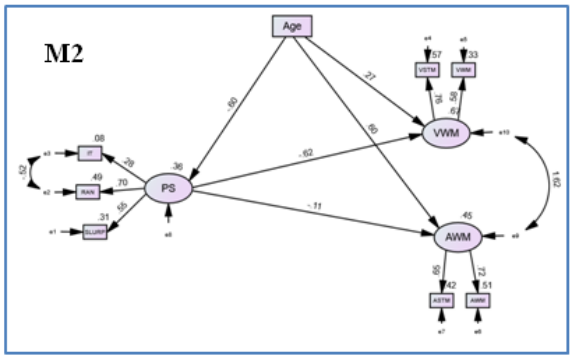

Figure 5: Diagrams of model 2 (M2). PS, processing speed; IT, Inspection Time (visual processing); RAN, Rapid Automatized Naming visual object verbalization (visual-verbal processing); SLURP, total duration in seconds (visual-motor processing); VWM, visual working memory; VSTM, visual forward digit; VWM; visual backward digit; AWM, auditory working memory; ASTM, auditory forward digit; AWM, auditory backward digit.

Model	$\chi 2$ testing	df	p	CFI	RMSEA
M1	20.174	14	.125	.96	.07
M2	10.534	14	.722	**1.000**	**.00**

Table 1: Fit statistics of the two models investigating the contribution of PS to WM

Note: $\chi 2$ = chi-square goodness-of-fit (if the value was not significant would indicate a good fit); df= degrees of freedom; CFI= comparative fit index (good fit when the value is greater than .95); RMSEA= the root-mean-square error of approximation (≤ .05 excellent model; between .05 and .08 good model and greater than .08 poor and unacceptable model)

Our findings illustrate that development in processing speed significantly contributes to visual (storage and processing) but not auditory WM in the second model that presents an excellent fit. One reason of the greater contribution of PS to WM is that, faster processing leads to faster rehearsal which in turns help maintaining greater amount of information to be stored in WM (Demetriou et al., 2014; Kail, 2000; Kail & Hall, 2001; Tourva & Spanoudis, 2020; Tourva et al., 2016). Our results are consistent with a wide range of literatures suggesting a significant contribution of processing speed to WM development (L. A. Brown, Brockmole, Gow, & Deary, 2012; Dang et al., 2015; Demetriou et al., 2014; Fry & Hale, 1996; Gray et al., 2017; Tourva & Spanoudis, 2020). Remarkably, WM in the majority of studies were assessed via visually presented stimuli tasks that required verbal recalling (L. A. Brown et al., 2012; Dang et al., 2015; Demetriou et al., 2014; Fry & Hale, 1996; Tourva & Spanoudis, 2020). Although, visual and auditory verbal are distinct domains of WM in younger children *per se*(Conant et al., 2003) most studies did not consider the nature of stored information (oral or visual) when investigating processing speed contribution to WM, and this might be the reason of the inconsistency results found by Kail and Hall (2001) when investigating PS contribution to WM using combinations of visual and auditory measures within the same model. Hence, our findings provide evidence that age related changes in processing speed improves only visual WM but not auditory. One possible interpretation is that visual stimuli need additional neuronal processing to be stored compare to auditory information that directly stored in the phonological loop (Crottaz-Herbette et al., 2004)

IV. CONCLUSION AND FUTURE DIRECTIONS

In conclusion, the current study provides evidence that improvement in auditory WM starts earlier than 8 years old as has been proposed from previous literature (Baddeley & Hitch, 2000; Baddeley & Logie, 1999; Hitch et al., 1989; Pickering, 2001). This improvement most likely linked to literacy and knowledge gained from school (Anderson & Wagovich, 2010; Ang & Lee, 2010; Conant et al., 2003; Pickering, 2001). Furthermore, to our knowledge, this is the first study investigating processing speed contributions to visual and auditory WM separately, and suggesting a critical contribution to visual WM alone which can be measured with visually based tasks (L. A. Brown et al., 2012; Dang et al., 2015; Demetriou et al., 2014; Fry & Hale, 1996; Gray et al., 2017; Tourva & Spanoudis, 2020). Further investigation is required to examine PS contribution to visual and visuospatial WM in early childhood with greater sample size. The future studies should involve other measures of visual and visuospatial WM since the current study has only used the digit span tasks.

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