Chapter

The Development of Visuo Spatial Working Memory in Children

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Abstract

The aim of this chapter will be to review the empirical research literature which has examined changes in children's employment of visual, spatial mnemonic and attentional processes when carrying out short term visuospatial working memory protocols. The chapter will evaluate the extent to which these processes can be effectively differentiated. An element of this consideration will be to ask whether such a focus directs research and conceptual attention away from working memory as an integrated system, where within a typical short term memory context, the child may bring multiple resources towards successful task performance. The review of the research literature will be embedded within the major theoretical accounts put forward to account for working memory development in children, multiple resources accounts, e.g., Baddeley (1986, 2007), Logie (1995, 2011); the embedded process account, Cowan (1988, 1999) and Oberauer's qualification of this account (Oberauer & Hein, 2011); the continuum model postulated by Cornoldi and colleagues, Cornoldi & Vecchi (2003); and the time-based resource-sharing account of Barrouillet and colleagues (2004, 2009).

Overview

A common consideration of working memory is that it functions to temporarily maintain and manipulate information in the service of a range of on-going cognitive tasks (e.g. Baddeley, 2012). Within this form of definition, *Visuo Spatial Working Memory* (VSWM) is viewed as the system which maintains and processes non-verbal information. The source of this visuospatial information varies dependent upon the particular conception of working memory, directly from perceptual information, or as activated, interpreted, long term memory content. One particular argument of this chapter will be that this definition of VSWM tends to be driven by the nature of the information media explicit in the working memory task demands, rather than the cognitive resources underpinning task performance. Within a child developmental context, the incongruency between the task surface visuospatial characteristics and the increasing recruitment of a diverse array of cognitive resources emerges as one of the defining characteristics of VSWM task performance change in children.

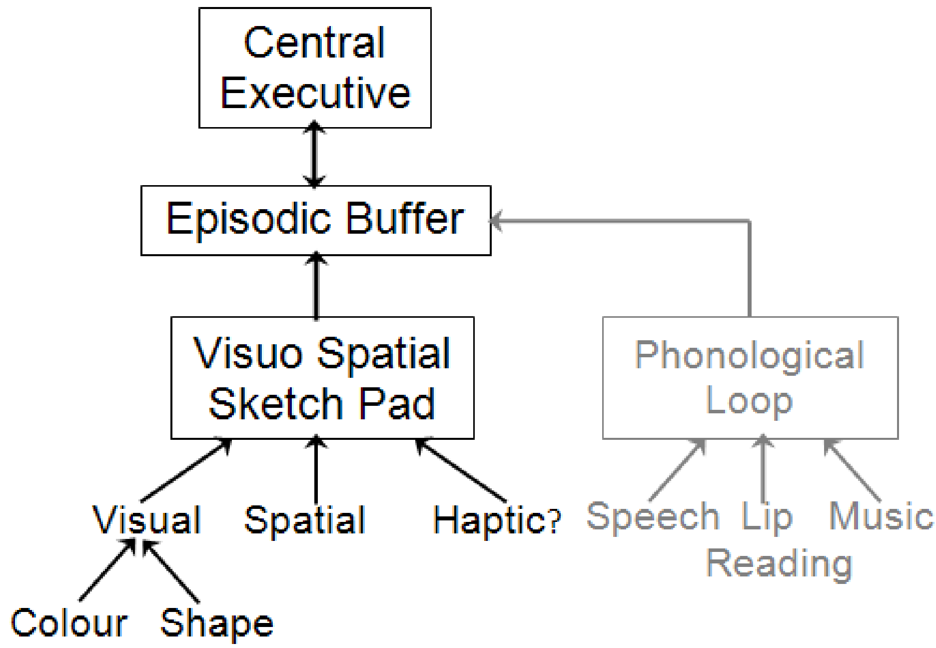
The chapter content will begin with a brief review of the major theoretical accounts of working memory, conventionally originating within an adult literature, but through the chapter a developmental perspective will be explicitly emphasised. This review will encompass multiple resources accounts (e.g. Baddeley, 1986; 2007, Logie, 1995; 2011); the embedded process account (Cowan, 1988; 1999) and Oberauer's qualification of this account (Oberauer & Hein, 2011); and the continuum model postulated by Cornoldi and colleagues (Cornoldi & Vecchi, 2003).Subsequently, the time-based resource-sharing account of Barrouillet and colleagues (2004, 2009) will be considered. The identification of these theoretical frames will be followed by a summary of the research literature which has aimed to identify changes in the efficacy of visual, spatial and executive or attentional processes within VSWM. The thrust of this summary will be towards conventionally labelled 'simple' span tasks, rather than the more attentionally engaged 'complex' span literature. Relevant evidence from processing speed accounts and developmental research with pictorial stimuli will be employed to demonstrate the potential for complex representation of visuospatial information. The final component of the chapter will attempt to interpret the research literature through an explicit consideration of the theoretical frames and research issues.

SOME THEORETICAL FRAMES

Multiple Resources Accounts

The original multiple resource or component working memory account suggested by Baddeley and Hitch (1974) envisaged three discrete resources, a *Central Executive* control process, a P*honological Loop* and a *Visuo Spatial Sketch Pad* (VSSP). This latter process was envisaged as "…retaining and manipulating images, and is susceptible to disruption by concurrent spatial processing…" (Baddeley, 1986). In more recent accounts the VSSP has been placed explicitly within the context of perceptual and long term memory processes (Baddeley, 2000, 2012). In these recent formulations, in addition to the domain specific slave processes there is also an *Episodic Buffer* process which retains integrated material or chunks which may be amodal or multidimensional in nature. Figure 1a identifies the architecture of the VSSP, emphasising the perceptual input to the store (a gateway account) and its interface with the Episodic Buffer. The VSSP is also subject to direct support and scaffolding from Long Term Memory (LTM) visual semantics and indirectly from LTM verbal semantics.

An alternative multiple resource model was proposed by Logie (1995, 2011). In this account there was an articulation of the VSSP component of the Baddeley (1974, 1986) model, a *visual cache* process for the storage of visual material and an *inner scribe process* for dynamic spatial representation and the active rehearsal of the passive visual material (See Figure 1b below) . This model demonstrated a striking symmetry in function between the verbal and non-verbal components of the model. However, one should note that perhaps the most fundamental difference between these two accounts is that in Logie's proposal, all of the information in working memory has gone through interpretation by the LTM (Knowledge Base) *prior* to entry into working memory. This would be conceived of as a *workspace* account rather than a gateway account (Logie, 1996). Thus within this perspective, the visual content of VSWM is likely to be in the form of fully integrated, fully bound objects. Whereas in the Baddeley account (Figure 1a), feature representation and bound representations may co-exist within the VSSP, e.g. colour, shape along with the integrated object (see also Baddeley, Allen & Hitch, 2011, Figure 6, p 1398).



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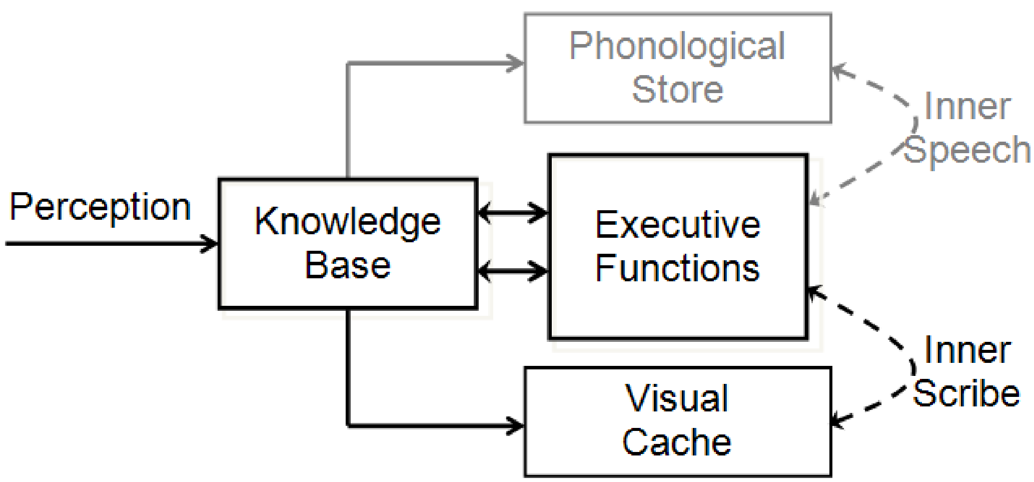

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Figure 1. a) The multiple resource account of Baddeley (2012); b) The multiple resource account of Logie (2011).

Embedded Processes Accounts

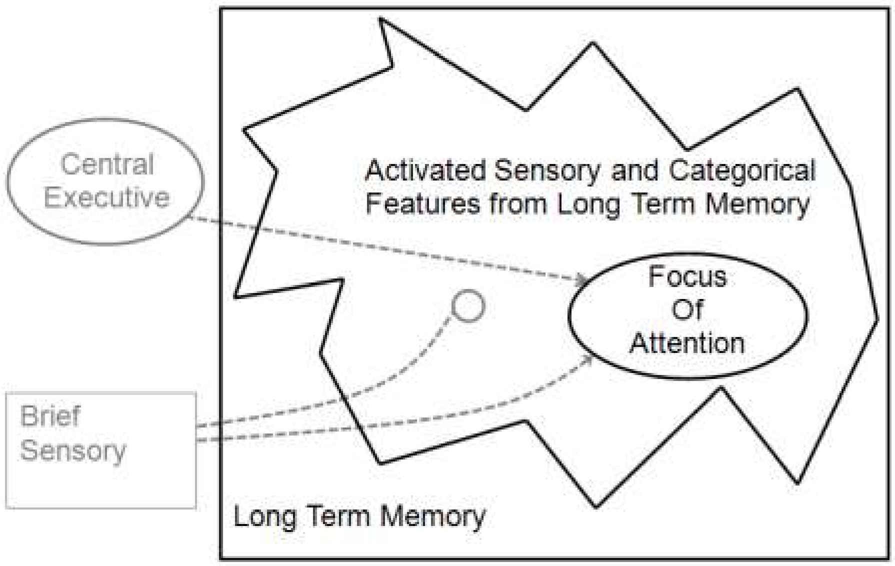
These accounts tend to be less modular than multiple resource accounts, sometimes labelled single (attentional) resource accounts. The earliest such model is the Cowan (1988, 1999, 2008; Engle, Kane, & Tuholski, 1999) *Embedded Processes* account. In this account working memory representation is seen as activated LTM sensory and categorical information. This activation level is above the typical level of LTM information; however information that is within the *Focus of Attention* is seen to have the highest level of activation (see Figure 2a below). This conceptualisation has been likened to the distinction between secondary and primary memory (James, 1890). The key process at work here is the attentional modulation within the focus of attention, what Cowan, Fristoe, Elliot, Brunner and Saults (2006) have labelled as the *scope* or *capacity* of attention. Unsworth and Engle (2007) have argued for a second attentional resource, associated with retrieval from secondary memory, activated LTM outside of the focus of attention (retrieval from within the focus is assumed not to require active processes). If comparisons can be made between this account and Baddeley's multiple resource account then one such comparison could be equating the focus of attention with a central executive process (as Cowan & Alloway, 2008, actually did, shown in Figure 2b).

Oberauer and Hein (2012) have modified the embedded processes by distinguishing between a broad focus of attention, of 3-4 items, in contrast to a component with a narrow focus of attention, specifically 1 item. This account accommodated prior experimental evidence which suggested that one chunk or item had privileged access and status. This is demonstrated in Figure 2b, which illustrates a schematic network in long term memory, with 5 items currently activate (shaded circles), and 3 items (a, b, & c) under the broad focus of attention, but 1 item receiving privileged access status (a).

Integrative Accounts

The two broad approaches identified above tend to emphasise modality specific and controlled attentional resources respectively. One account, the Continuum Model (Cornoldi & Vecchi, 2003) emphasises both modality specific stores and controlled attention. In this model, shown in Figure 2c, there is a vertical continuum varying in the degree of attentional control needed to carry out the task at hand. At the passive end of the continuum, the lower portion of the figure, where maintenance and storage only is required, the authors envisage quite discrete modality specific processes. As task demands increasingly require more controlled attention, a movement up the continuum, the resources recruited become increasingly amodal and generic. Whilst this appears in many ways similar to the Baddeley multiple resource account discussed above, it makes more explicit the notion of a flexible allocation of attention to task completion (Kahneman, 1973) and consequently undermines the naive categorisation of tasks into *Simple* and *Complex*. The majority of VSWM tasks will inevitably vary in their requirements for maintenance and controlled attention resources.

Whilst the theoretical accounts identified above tend to be formulated and considered within a young adult context, the content of this chapter will also consider accounts specifically associated with lifespan development, e.g. the putative contribution of inhibitory processes (Hasher, Lustig & Zachs, 2007), and the contribution of Speed of Processing (SOP, Fry & Hale, 1996; Kail & Salthouse, 1994). In particular, a more recent account the Time-Based Resource-Sharing model proposed by Barrouillet and colleagues (2004, 2011) will be considered. This framework has been successfully applied within a child development context (e.g. Camos & Barrouillet, 2011).



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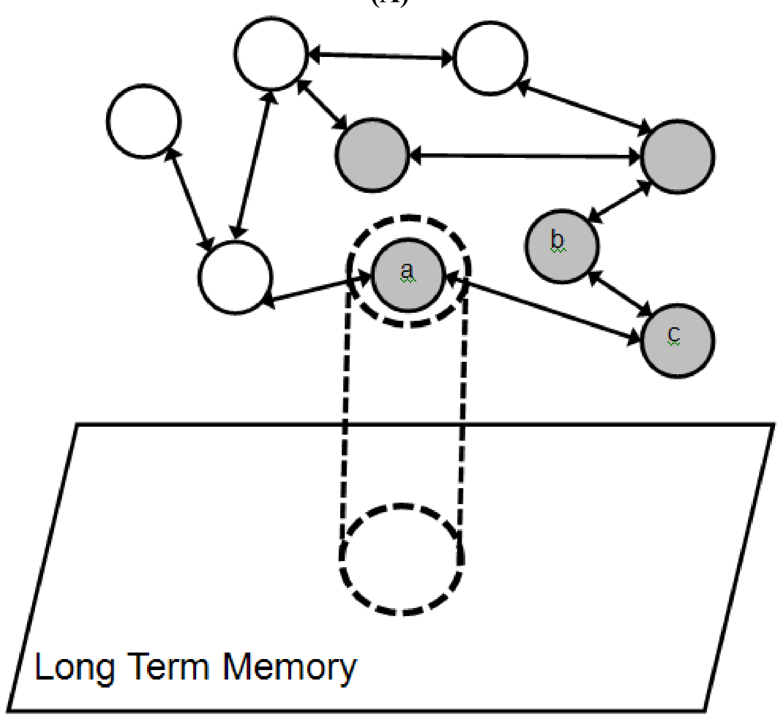

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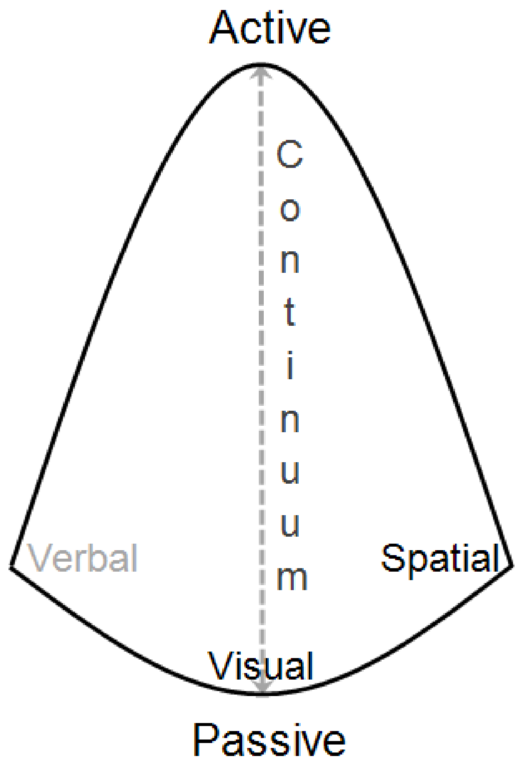

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Figure 2. a) The embedded processes account of Cowan (2008???); b) The three embedded component model (Oberauer & Kliegel, 2012); c) The Continuum Model (Cornoldi & Vecchi, 2003).

THE DEVELOPMENT OF VISUAL AND SPATIAL WORKING MEMORY TASK PERFORMANCE

Visual Working Memory Research Findings

A large number of research protocols have been employed in order to assess visual working memory in children, the stimuli have ranged from visual matrix patterns (Della Sala, Gray, Baddeley, Allamano & Wilson, 1999; Phillips & Baddeley, 1971; Pieroni, Rossi-Arnaud, & Baddeley, 2012), coloured patterns arrays (Luck & Vogel, 1997; Riggs, McTaggart, Simpson, & Freeman, 2006), to static and dynamic arrays (Mammarella, Pazzaglia, & Cornoldi, 2006; Pickering, Gathercole, Hall, & Lloyd, 2001). This current section will focus on a number of research protocols, and then in the final section discuss the implications of the results from the wider empirical context. It is worthwhile re-iterating that the vast majority of these protocols were designed for young adult research rather than as a tool for understanding individual differences associated with the lifespan and child development in particular.

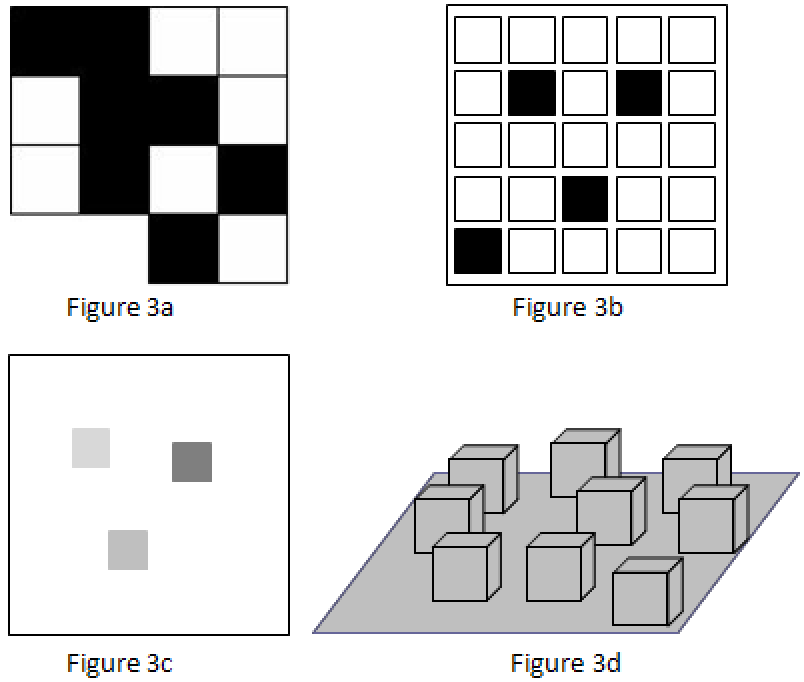
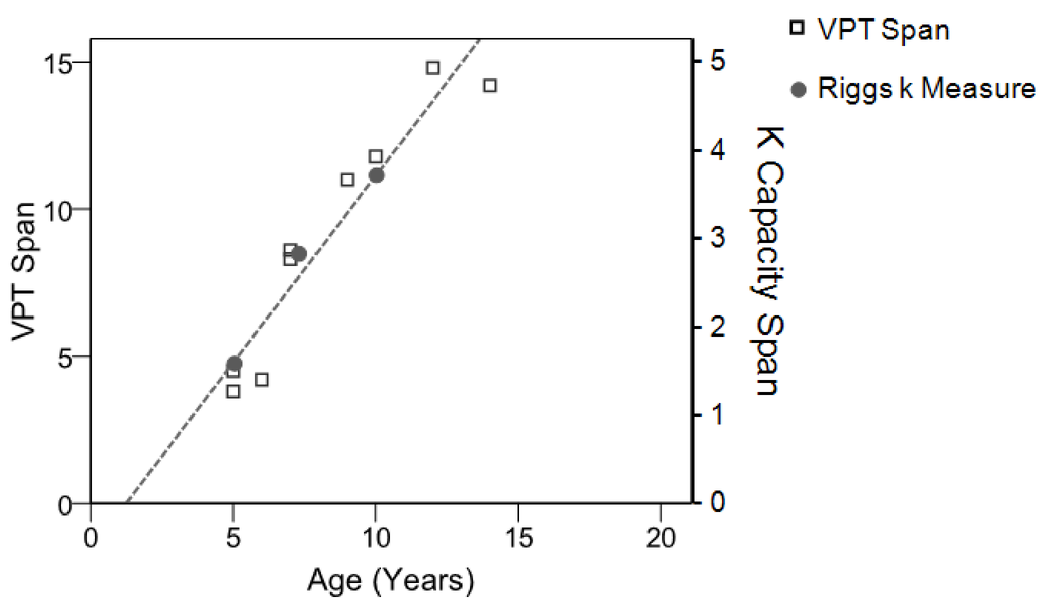


Figure 3. Visuo Spatial Working Memory Task Stimuli.

Three of the common visual working memory protocols are illustrated in Figure 3 above. The visual matrix or Visual Pattern Test (VPT) protocol is shown in Figure 3a, typically a matrix pattern where 50% of the cells are black, 50% are white. The pattern is shown for a period of time (encoding duration) then retained (maintenance interval) then retrieved either though a recall context or recognition process. There is variability in the protocol formats and proportion of black cells may vary, as in the matrix pattern shown in Figure 3b, a protocol employed by Pieroni and colleagues (e.g. Pieroni et al., 2011; Rossi-Arnaud, Pieroni & Baddeley, 2006). In addition, encoding time and maintenance may vary between studies, or actually be the focus of experimental manipulation (e.g. Wilson, Scott, & Power, 1987). A common element is the use of span measurement where the number of black cells is increased until the participant failed to meet the criterion. It should be noted that there is also variability in how one measures the span level, with implications for the reliability of the data (Friedman & Miyake, 2004; St Clair-Thompson, 2010). Another commonly employed protocol in adult research, the visual array procedure of Luck and Vogel (1997) has also been employed within a child developmental context. The conventional array format is shown in Figure 3c, the array size can contain between 1-6 items, is typically briefly presented (< 1 second) and the maintenance interval also tends to be brief (0.5-3seconds). This protocol has been employed in a number of child developmental studies, e.g. by Cowan et al. (2005) and Riggs and colleagues (Riggs et al., 2007; Riggs, Simpson & Potts, 2011). Visual working memory capacity in this protocol was measured in terms of k, derived from array size, and the hits and false alarm rates in task performance (see Pashler, 1988).

Figure 4 identifies the general developmental trajectory for visual matrix span development in children. The VPT span data points are drawn from three studies, Wilson et al. (1987), Logie and Pearson, (1997) and Miles, Morgan, Milne and Morris (1996). Despite differences in the precise characteristics of their respective protocols the combined data neatly fits a developmental function which indicates a rapid increase in VPT span performance from the age of 5 years through to 15 years of age. The graph also reveals another interesting characteristic of the research findings, that the 15 year old children are performing at level equivalent to adults in two of the studies (Wilson et al. and Miles et al.). However, this performance level is well above the typical young adult level in the VPT noted by Della Sala, Gray, Baddeley and Wilson (1997). In their sample of 345 adults the mean performance was 9.08. This discrepancy could be due to the recall protocol in the Della Sala et al task as opposed to the recognition data in Figure 4 (see Logie & Pearson, 1997, for a direct comparison of span performance in the two retrieval contexts). Other differences in terms of differences in progression criteria, encoding or maintenance duration, or of pattern configuration in the form of complexity could also account for this difference and the latter will be discussed at length below.

Also shown in Figure 4 is the data from the Riggs et al. (2007) study which employed the visual array format adopted from Luck and Vogel (1997). Three age groups were employed in this study, 5, 7, and 10 years of age. The developmental function overlaps with the VPT function only when the two scales are equated for adult performance level. Typically young adults achieve a k score of ~ 4 items, a quantitatively similar level of performance to that with the matrix employed by Pieroni et al. (2011). However, the k value is significantly smaller than the span level typically found in the visual matrix procedure. Identifying the factors which could account for this discrepancy lies at the heart of the discussion in the next section.



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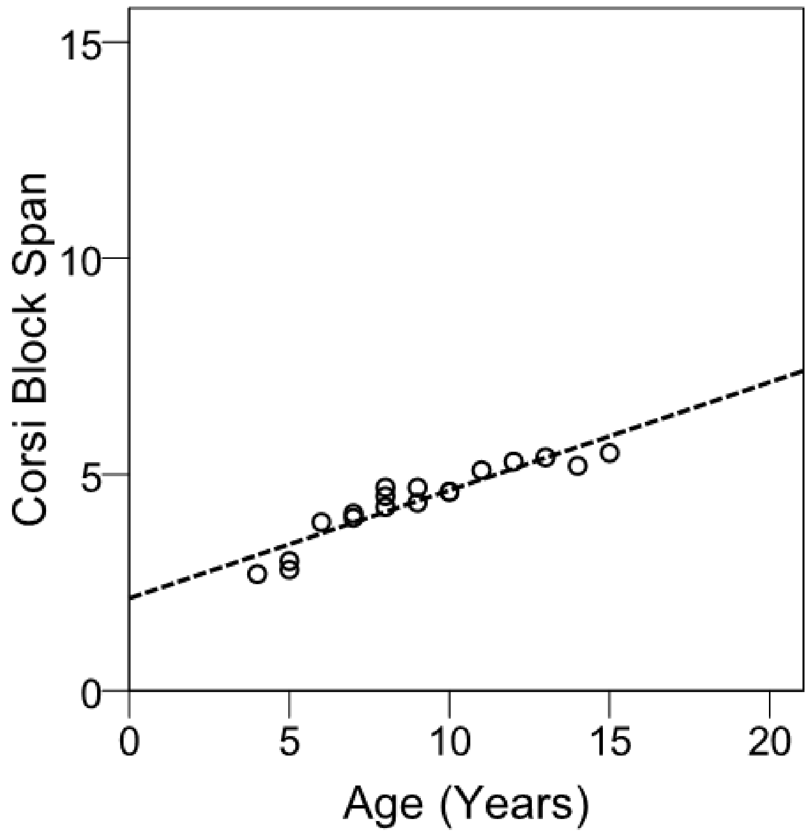

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Figure 4. a) The Developmental trajectory associated with the VPT Span and k Capacity measures; b) The developmental trajectory associated with the Corsi Block task.

The developmental work by Pickering et al. (2001) explored a particular characteristic of the array during the encoding of visual matrix patterns, whether the black cells were presented simultaneously on the screen (static version) versus the appearance of individual cells in a sequence of screen shots (dynamic version). The age associated development, as measured by number of trials correct, demonstrated a large increase between the ages of 5-10 years, congruent with the improvement shown in Figure 4 with VPT span data. However, the improvement in the dynamic version, although significant, was not as large as that of the static version. This pattern of *developmental fractionation* (Baddeley & Hitch, 2000) was mirrored in static and dynamic versions of a maze task, and led the authors to conclude that static and dynamic sub component processes were present in visual working memory. Their conclusion was congruent with the spatial-simultaneous versus spatial-sequential differentiation in the Continuum model (Cornoldi & Vecchi, 2003). However as Pickering et al conceded, their dynamic matrices task possessed the characteristics of the Corsi Blocks task (see Figure 3 d), a task conventionally taken to be a measure of Spatial working memory (Della Sala et al., 1999; Logie, 2011). The next section will consider the research findings associated with Corsi and other measures of spatial working memory.

Spatial Working Memory Research Findings

One of the major prototypical spatial working memory tasks conventionally employed in developmental research has been the Corsi Blocks task (Milner, 1972). The Corsi task (see Figure 3d above) was originally constructed as a complementary task to the digit span task within a clinical context, in order to reveal hemispheric specialization; more specifically to make demands upon the temporal lobe and hippocampus in the right hemisphere (Milner, 1972). It shares two major elements in common with the digit span task: the sequential presentation of the item (in the Corsi task, the sequential tapping of individual blocks) and the demand for accurate serial order in the recall of phase of the task. More recently, researchers have employed PC generated Corsi or spatial span procedures, but as with the VPT task, variability in the protocol exists across studies (Berch, Krikorian & Huha, 1998). The most common outcome measure is the span measure, typically ascending, whereby the number of taps is increased until the participant fails to meet the progression criterion.

The data from 3 studies are superimposed in Figure 4b, data from Orsini, Capitani, Laiacona, Papagno, and Vallar (1987), Isaacs and Vargha-Khadem (1989), and Logie and Pearson (1997). The data points again fit onto the regression function despite differences in protocols. The Corsi Block Span scale in Figure 4b has been adjusted to match that in 4a, where the VPT is plotted. This allows a more direct comparison and suggests that the age associated improvement in the Corsi is not as large as that of the VPT developmental change. This was addressed directly by Logie and Pearson who revealed a significant interaction in the task (VPT vs Corsi) by age group analysis. This was taken by the authors as an indication of *developmental fractionation* (Baddeley & Hitch, 2000) and evidence for differentially age associated development in two processes; namely the visual cache and inner scribe (Logie, 1995, 2011). Interestingly, this pattern of results is similar to that reported by Pickering et al. (2001), however, the demonstration of developmental fractionation was interpreted differently (see above). One should also note that there is evidence of concurrent validity for the Corsi using other measures of spatial memory in children (e.g. Pentland, Anderson, Dye & Wood, 2003)

Postma and De Haan (1996) proposed a three-process account of object location or spatial memory; a *position only* process which allowed the precise spatial location of an object, based upon a coordinate spatial relations process; an *object-to-position* process which allocates object to locations, a process which would draw verbal as well as visuospatial working memory processes; and a *combined* process which integrates the two processes above. Cestari, Lucidi, Pieroni and Rossi-Arnaud (2006) investigated the age associated trajectories in 6, 8 and 10 year old children. They found that position only and object-to-location processes showed early improvement, between 6-8 years, however, the combined process developed later between 8-10 years. Thus, their finding suggested the presence of significant age associated improvements across the age groups, but with interesting differences in trajectories of these processes.

ISSUES IN THE INTERPRETATION OF VISUAL AND SPATIAL WORKING MEMORY RESEARCH FINDINGS

A fundamental question of any of these studies is the extent to which the research question and data allow one to identify which processes are actually changing in child development (Cowan & Alloway, 2008; Hamilton, Coates & Heffernan, 2003). If one employs the frameworks in Figure 1 as a filter for this interpretation, complexities are immediately identified in the process. As Conway et al (2006) suggest, the first issue concerns the diversity of conceptual framing employed in the working memory literature and how this undermines the mapping '…from constructs to mechanisms to measures…' (p4). An example of this is evident in the labelling of VSWM tasks (as well as verbal tasks) as 'simple' and 'complex'. Within a multiple resource account such as Baddeley (1986) and Logie (1995) simple tasks would presumably make exclusive demands upon the 'slave' systems such as the VSSP, Visual Cache or the Inner Scribe. Within an embedded processes account (e.g. Cowan, 1999) or continuum account (Cornoldi & Vecchi, 2003), simple tasks would have the capability of demanding executive or attentional resources, but less so than those tasks labelled as complex. Thus, tasks such as the VPT or Corsi may recruit visual and verbal semantics (Baddeley, 2000) or processes such as recoding, chunking, rehearsal (Engle et al., 1999). There is extensive dual task evidence in adults to indicate that tasks such as the Corsi and VPT are impaired when secondary task interference targets executive or attentional resources (Fisk & Sharp, 2003; Rudkin et al., 2007; Vandierendonck et al., 2004; Vergauwe et al., 2009). More importantly research has indicated that visuospatial task performance in children can be affected by attentional and non-domain specific interference. In tasks designed to mimic the cognitive demands of the VPT and Corsi tasks, Hamilton et al. (2003) employed verbal fluency (LTM retrieval) interference during the maintenance phase and observed that both visual and spatial task performance was significantly impaired. The impact of this verbal secondary task suggests a role for amodal resources in these VSWM task demands. Thus, even these simple tasks appear to require maintenance *and* processing resources, as indicated in early accounts of the VSSP (e.g. Baddeley, 1986).

The Contribution of Processing Speed to Task Performance

Early accounts of individual differences associated with child development (and adult ageing) have emphasised the importance of processing speed as a key source of change. Case, Kurland and Goldberg (1982) suggested that total capacity (*M capacity*) remained constant over development, however they suggested that processing speed may improve leaving more space for storage. This may account for why Hamilton et al (2003) also noted that a simple measure of processing speed, articulation rate, was significantly correlated with the younger children's VSWM task performance in their study. The processing speed account was qualified by Towse, Hitch and Hutton (1998) in their *task-switching* account of working memory development in children. They accepted that processing speed could impact upon span performance but argued that this was because information being maintained in working memory was subject to rapid decay and therefore quick processing meant that children could access this decaying information more promptly, and were thus more efficient in reconstructing the information. Hitch, Towse and Hutton (2001) went on to identify that simple accounts of processing speed could not account equivalently for discrete complex span procedures, e.g. operation span versus counting span (see also Cowan, Elliot, et al., 2006). More recently Barrouillet and colleagues (e.g., Barrouillet & Camos, 2011; Portrat, Camos & Barrouillet, 2008) have suggested that both resource sharing and trace decay contribute to working memory task performance, they labelled this a Time-Based-Resource-Sharing (TBRS) account (Barrouillet, Bernardin & Camos, 2004). They argued that attention was required for two key processes in working memory, to carry out the processing demands and to actively maintain (or reactivate) the information being maintained.

The Barrouillet argument differed from Towse et al by implying that attention could be allocated to refreshment or reactivation ant any point during the processing phase of a task if the cognitive load of the processing component did not demand sustained attention. Thus, they demonstrated that it is not time of the processing phase per se which matters, but the extent to which attention is occupied during this phase. In a recent child developmental study Gaillard, Barrouillet, Jarrold and Camos (2001) provided evidence that in order to make working memory span performance in 8 and 11 year olds equivalent, not only had processing efficiency to be controlled for but also the time available for reactivating memory traces needed to be equated. This study identifies the importance of the active maintenance of information in working memory and indicates that in younger children this is attentionally demanding and requires more time. The focus upon refreshment and rehearsal within children is developed below.

Visual and Verbal Representation in VSWM Pictorial Task Performance

Recent research has focused upon the distinction between rehearsal processes and refreshment processes in both adults (Camos, Mora & Oberauer, 2011) and in children (Camos & Barrouillet, 2011; Tam, Jarrold, Baddeley & Sabatos-Devito, 2010). The work of Camos and Barrouillet (2011) looked at changes in children aged 6 and 7 years in how they maintained verbal labels related to pictorial stimuli. Their procedure manipulated both cognitive load and the processing duration, and is demonstrated in Figure 5 below.

The standard procedure involved being exposed to animal pictures and then subsequently recalling the names of the animals, thus the verbal recall protocol was explicit in the procedure. In the baseline condition, shown in 5a, the children were exposed to an animal stimulus (bear) for 2000ms, then had to name the colour of a smiley face, within a 4000ms processing period, before being exposed to the second animal stimulus (cat). In the heavy cognitive load condition, Figure 5b, between the presentation of animal stimuli, the children had to name the colour of two smiley faces within a 4000ms processing period, thus the cognitive load was doubled in the condition, but the processing duration was the same as in the baseline condition. In the final condition, the long processing duration condition shown in Figure 5c, the children, between the presentation of animal stimuli, had to name the colour of two smiley faces within a 8000ms processing period. This condition therefore had the same cognitive load as the baseline, but a processing duration twice as long as the baseline.

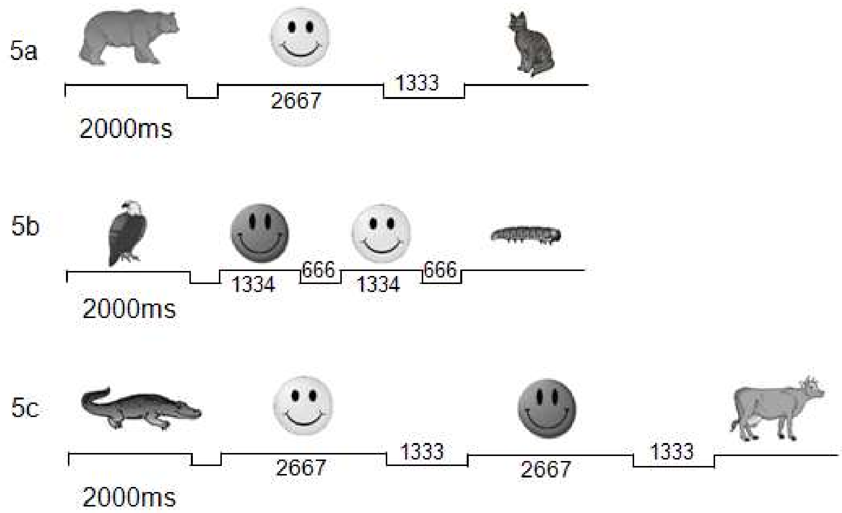


Figure 5. Investigating the impact of cognitive load on attentional refreshment, derived from the Camos and Barrouillet (2011) protocol.

The Camos and Barrouillet (2011) findings suggested that for the younger children aged 6yrs, the change in cognitive load did not affect performance, but the increase in processing duration did impair performance. In contrast, with the older children aged 7yrs, only the cognitive load manipulation affected task performance. The authors argued that this pattern of results reflected a qualitative shift from a passive rehearsal process in the younger children to an active maintenance or refreshment process in the older children, when cognitive load manipulation led to impaired performance. They also suggested that the results in the younger children could be accounted by the task-switching account of Towse, Hitch and Hutton (1998), whereas the cognitive load effect observed in the older children could be more readily explained with reference to their Time-Based-Resource-Sharing account. The authors also interpreted their results in terms a process of temporal decay rather than interference.

Much of the research identified above regarding processing speed involved complex span procedures, and much of the research on refreshment and rehearsal has employed verbal material, and thus its relevance to Visuo Spatial Working Memory task performance may not at first glance appear obvious. However, there has been a long lasting debate within the VSWM developmental literature concerning the nature of visual and verbal representation with visuospatial material such as objects. The early work of Hitch and colleagues looked in detail at the presence of multiple representations with pictorial stimuli (e.g. Hitch, Halliday, Schaafstall & Schraagen, 1988; Hitch, Woodin, & Baker, 1989). Hitch et al. (1988) contrasted visual working memory in 5 and 10 years olds for line drawings of common objects. Through a systematic set of experimental procedures investigating serial position curve attributes, visual similarity and retroactive inhibition effects they established that with pictorial stimuli, the 10 year olds were more reliant on phonological representation. However, even in the youngest children, phonological representation could be employed, and in the older children, some visual representation was still employed (Hitch et al., 1989).

The complexity of pictorial representation through childhood is illustrated in the work of Palmer (2000) who manipulated visual and phonological similarity in tasks demanding the maintenance of line drawing pictorial stimuli similar to the Hitch et al. (1988, 1989) procedures. Palmer looked at the representation of the pictorial images in children aged from 3 to 8 years. She observed that the youngest children were not, in the main, susceptible to either visual or phonological similarity effects. However, from the age of 3 to 6 years, a visual coding strategy, evidenced by a visual similarity effect (VSE), was present. In the 7 year olds, both visual and phonological similarity effects (PSE) were apparent, some children demonstrated only a VSE, some only a PSE, and some both. A second study found a similar pattern of complexity across a 3 year sequential period. Palmer concluded a particular sequence of coding occurred, an early phase where no strategic process is at work, performance being facilitated by LTM activation associated with the pictorial stimuli, followed by visual then phonological coding, where a central executive process allocates attention to temporarily activated LTM representations. Palmer argued that in older children, executive processes would inhibit the visual representation leading to phonological dominance. The emphasis in this study was of VSWM operation within a workspace account.

Henry, Messer, Luger-Klein and Crane (2012) identified a major issue with the visual/phonological research identified immediately above, the implicit and explicit cueing of phonological representations of the pictorial stimuli. Identifying research which demonstrated PSE in very young children, Henry et al. discussed how the observation of children's spontaneous use of phonological recoding may be undermined by the child's explicit verbal labelling of the stimuli, prior to the onset of the procedure, and the requirement for spoken recall at retrieval. The procedure began with the experimenter naming the objects, and then subsequently employed a sequential presentation of a set of pictures, followed at retrieval by a non-verbal response, pointing in the same sequence to the target stimuli on a response board. The results suggested that the 4-5-year olds did not show any evidence of visual, phonological, or semantic similarity effects, nor word length effect. However, the 6-8-year olds did demonstrate PSE and word length effects. A second experimental replication, using potentially a more sensitive measure, the total number of items correct being the dependent variable (Friedman & Miyake, 2004; St Clair-Thompson, 2010) found a slightly different pattern with a significant VSE in the high achieving sub-group (cluster) of the sample. A third experiment confirmed the presence of PSE and word length effects in children with high task performance. Henry et al. (2012) concluded there was strong evidence for phonological coding of the pictorial stimuli, evidence by PSE and word length effects; a recoding process which develops gradually in children aged between 5-6 years. In 7-year olds, performance was related to the children's self-report of phonological coding. There was only weak evidence for visual representation, and marginal evidence for dual visual/verbal coding.

What is consistent in the developmental research employing pictorial stimuli is the finding of increasing phonological representation of the stimuli through childhood, with the declining importance of visual representation. However, it clear that issues associated with specific protocols may constrain one's interpretation of the findings. Henry et al. (2012) point to the potential confounds arising from a procedure where the child explicitly identifies the names of the pictorial objects and has to provide a spoken response at retrieval. However, in a context where the familiar objects are presented, it is clear that there is always the potential for visual and verbal LTM semantics to be available to the child, the question then becomes at which stage will the child be able to spontaneously make us of these LTM resources? Thus, any naming the pictures, by participant or experimenter may merely emphasis the verbal semantics associated with the stimuli, regardless of the retrieval protocol. An additional issue associated with the procedures employed in the pictorial research has been the sequential presentation of the stimuli.

Whilst in some research, simultaneous versus sequential stimulus presentation appears to have no major impact upon span (Cowan, AuBuchon, Gilchrist, Ricker & Saults, 2011), the nature of the task demand does change significantly, particularly if the recall requires correct serial order (Avons, Ward & Melling, 2004; Jones, Farrand, Stuart & Morris, 1995). There is perhaps the requirement for more controlled attention as the representation is updated after each event. Extensive research has suggested that with sequential presentation of visuospatial material the typical recency effect is restricted to the last item (e.g. Avons et al., 2004; Phillips & Christie, 1977). An argument made by Phillips and Christie is that recency item and pre-recency items reflect short-term and long-term memory representations respectively. Interestingly, in the context of child studies, Phillips and Christie noted that the single item recency occurs with short and long lists, the shorter length necessarily being employed in child studies. The presence of this recency component in sequentially presented protocols is evident in the Hitch et al. (1988) study. Whilst in adults, the retrieval context, backward retrieval or probed stimulus does not necessarily influence task performance (Phillips & Christie, 1977); the retrieval protocol with young children may be more problematic. Hitch et al. (1988, study 2) demonstrated that forward or backward recall of sequentially presented stimuli substantially impacted upon the serial position curve (SPC), the recency effect almost completely disappeared with forward recall in both the 5 and 10-year old groups. This would suggest that the short term component of visual memory is minimised in the forward recall protocol. In addition Hitch et al. noted (study 3) that visual retroactive interference had its major effect predominantly upon the recency item. Thus, with children, investigation of a visual representation in short term memory may be seriously compromised by forward recall within a sequential presentation protocol.

The initial developmental research literature discussed above focused upon tasks such as visual matrices, Corsi blocks and visual arrays where the explicit verbal characteristics of the stimuli are minimised, thus, it could be possible that in these tasks, verbal recoding is minimised. However, even with the VPT stimuli, verbal semantics can be employed to give meaning to the black and white cell configurations (Brown, Forbes & McConnell, 2006). It is clear from a range of paradigms that participants will attempt to reduce the complexity of the stimulus by organising and chunking the stimuli in order to give more meaning in the form of verbal and visual semantics to the pattern. Sun, Zimmer and Fu (2011) identified two elements associated with complexity in visual patterns; *physical complexity* associated with low level or perceptual cues explicit in the pattern and *perceived complexity* associated with the relevant expertise brought to the study by the participant, this would include the notion of visual and verbal semantics identified above. Research has established the importance of low level cues in the form of symmetry, grouping, and configuration upon VSWM task performance (e.g. De Lillo, 2004; Kemps, 2001; Rossi-Arnaud, Pieroni, Spataro & Baddeley, 2012). Whilst it is possible that these low level cues could be utilized effectively early in child development, the strategic utilization of verbal and visual LTM semantics is likely to demonstrate progress through childhood.

Although it has been suggested in adults that verbal interference does not necessarily impair VSWM task performance (Morey & Cowan, 2004), Palmer (2000) has argued that in children the use and integration of visual and verbal information in VSWM task performance was likely to arise though attentional processes. The integration of features within or between modalities may be considered to be a primary or primitive role of an executive process ‘dual task’ function (e.g. Baddeley, 1996), however there is evidence to suggest that the efficacy of some elements of binding increase through childhood (Brockmole & Logie, 2013; Cestari et al., 2006).

Issues in Identifying VSWM Capacity Changes in Childhood

The content immediately above has highlighted some of the putative issues when trying to understand what changes in VSWM task performance in children. This section will focus upon research which has attempted to disentangle the potential factors underlying VSWM task performance in children.

A starting point is to consider how and where attentional processes could contribute to VSWM task performance. If working memory is seen as a workspace, where content is interpreted prior to entry into VSWM, then attentional processes could potentially constrain the entry process into VSWM; an *encoding* impact. Vogel, McCollough and Machizawa (2005) provided evidence in adults that a key process in working memory efficacy is the inhibition of (goal) irrelevant stimuli, so preventing them from loading working memory. Cowan et al. (2006) would have labelled this a *control of attention* process. The focus of attention (see Figure 2a) would act to maintain a number of activated items or chunks; Cowan et al. labelled this aspect the *scope of attention*, and is at work during the *maintenance* phase of working memory. However, other attentional processes could also be at work during the retention phase, organising the information, e.g. forming complex chunks informed by both visual and verbal semantics, and these could be considered further attentional control processes. The presence of such control processes may lead to an overestimate of the scope of attention (Cowan, 2010) In addition, there is also potential for attentional influences at the point of *retrieval*, both in terms of the retrieval processes per se (Unsworth & Engle, 2007) and the retrieval context (e.g. single probe versus full screen recognition, Wheeler & Treisman, 2002). It could be argued that the impact of the retrieval context is less considered in the research literature than the other two phases of the working memory task process.

Recent work by Cowan et al. (2011) has attempted to disentangle the contribution of encoding and capacity in VSWM development. These authors established a procedure whereby children had to allocate attention to a subset of objects (e.g. circles over triangles) within an array. This manipulation allowed the authors to consider what proportion of target stimuli were maintained and the number of non-targeted stimuli remembered, the latter an indication of inefficient attentional filtering at encoding. The study employed three age groups, 6-9 years, 11-13 years, and 18-21 years. The results suggested that the relative attentional filtering efficiency of the youngest age group was equivalent to that of the adult group. However, despite the lack of age difference in this attentional control process, there was an age associated improvement in the task performance. The authors interpreted this as indicating an improvement in the visual memory capacity of the children, i.e. an increase in the scope of attention. It is difficult to consider where in the Visual Patterns Test, Corsi task, or in the original Luck & Vogel (1997) visual array protocol, an inhibitory filtering process would be as important for task performance, as all of the information presented is meant to be remembered and retrieved. However, there may be a temporal constraint within the encoding process associated with attentional disengagement (Fukuda & Vogel, 2011) and should this occur in a child context with brief presentation times then performance in any VSWM task will suffer.

An important characteristic employed in the Cowan et al. (2011) study was the use of verbalization in some of the conditions, either the target object's colour was identified, or the child had to say 'wait' after each item was presented. The former condition, naming the colour, could be seen as a way of implicitly cueing the participant to consider the use of verbal labelling, and indeed in both child groups led to an improved k-capacity score. However the 'wait' utterances manipulation was viewed by the authors as a protocol mimicking articulatory suppression, and indeed in *all* 3 age groups this reduced the span level. These results suggest that even with nonverbal stimuli, verbal semantics can be employed by children, but more importantly for the authors, that in the absence of these phonological labels, capacity continued to increase through childhood. It is clear that in the VPT, Corsi and Luck and Vogel protocols, the presence of verbal semantics could inflate performance.

Perhaps more important for these conventional VSWM protocols is the extent to which visual, verbal, and configurational cues could lead to elaborated organization and chunking in order to reduce the visual complexity, a process of compression (e.g. Kemps, 2001; Rossi-Arnaud et al., 2012). This would lead to improved VSWM task performance, not necessarily because of an increase in the scope of attention, the number of chunks, but rather that compression has led to a richer quality, i.e. more information within the chunk. Research by Cowan, Hismjatullina et al. (2010) has attempted to disentangle the contribution of capacity and compression processes to changes in VSWM performance in children. In their experimental protocol, pictorial stimuli were initially associated as pairs or triplets (as opposed to singletons) in a familiarisation phase prior to becoming elements of a memory procedure. The results suggested that the extent to which adults developed rich (compressed) chunk representation was greater. However, whilst controlling for this improvement the authors were able to observe that from the 8 year-old group to adulthood, there was an increase in the number of chunks that were utilized, thus capacity was still improving. This was also the case when compared with adults who were subject to articulatory suppression. Therefore, although visual (and verbal) semantics can improve VSWM task performance through improving the richness or quantity of information within a chunk, the scope of attention independently shows developmental improvement.

This suggests that in the matrix stimuli of Kemps (2001) and Rossi-Arnaud et al. (2012) and the Luck and Vogel (1997) array formats, there is scope for some development of chunk compression efficacy through childhood, potentially inflating an accurate measure of capacity. This is more clearly seen in the performance of children in the conventional VPT task where by the age of 5 years, children are remembering more black cells than the typical adult visual memory capacity level (see Figure 3 above). What is required in all of this developmental research is the development of protocols where chunk compression efficacy can be identified and a distinction made between perceptually driven visual organisation (physical complexity in the pattern) and perceived complexity (Orme & Hamilton, submitted; Sun et al., 2011), where on-line compression activity may occur in the absence of explicit LTM priming which was the case in the Cowan et al., (2010) study.

Beyond a Quantitative Approach to VSWM Development

The emphasis in much of the conventional VSWM research identified above and in the pictorial stimuli research has been upon the VSWM capacity or scope of attention associated with child development. This quantitative approach has been complemented by research which has looked at how children may recruit any cognitive resource pertinent to task completion. This research has made use of the functional architecture of working memory, whereby processes endogenous to, or exogenous to working memory may be recruited (Baddeley, 2000; Hamilton et al., 2003). This research has adopted a more qualitative approach, a consideration of which process contribute to task performance and is seen in many of the studies discuss above. Examples are where phonological representation is explored (e.g. Hitch et al, 1988), attentional control processes are examined (e.g. Cowan et al., 2011) or the contribution of retrieval from secondary memory is considered (e.g. Hamilton et al., 2003).

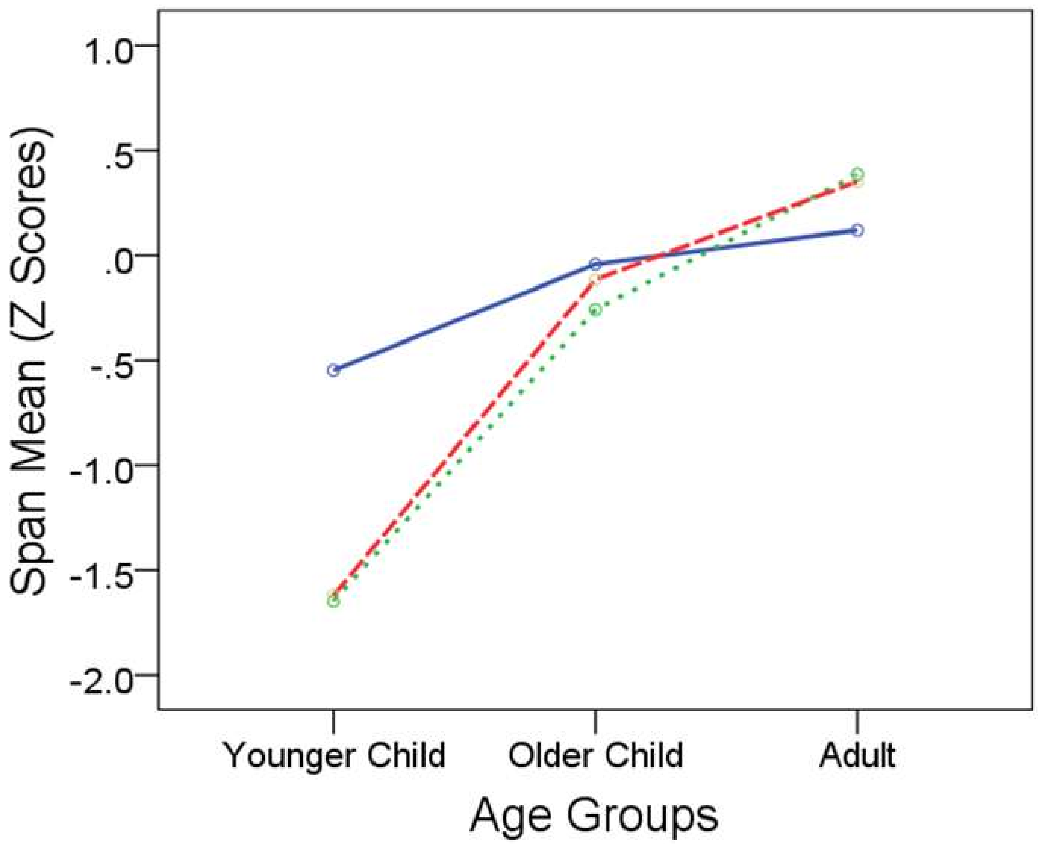
A further qualitative approach to investigating short term visual memory has been adopted which emphasises the nature, rather than the quantity, of the representation. An approach which assesses the quality, high fidelity and fine detail maintained in the representation (Hamilton, 2011). The protocol may involve a change detection paradigm where the memory stimulus is initially presented then a subsequent stimulus only differs by a very small degree. The participant has to judge whether a change has occurred or not. In the Thompson, Hamilton et al. (2006) study, the Size JND procedure employed such a protocol. The memory stimulus was a single yellow square, at test, another yellow square was presented during retrieval and this stimulus this could be either the same size or a different size; however the size difference could vary in steps from 40% to 5%. In order to detect a change of 5%-10% the participant would have to maintain a high fidelity representation of the initial memory stimulus. In the Thompson et al study, a delay of 4 seconds between memory and test item led to a performance level of 15%, i.e. for most participants, a smaller change of 5% or 10% was beyond the quality of their representation. Such high fidelity representation was also explored by Dean (2007), Dent (2010), and McConnell and Quinn (2004) with texture, colour and size attributes respectively. A consistent observation in these studies has been the impact of Dynamic Visual Noise (DVN) interference upon the performance. This is an interesting observation given that DVN interference does not appear to impact upon VPT performance (e.g. Andrade, Kemps, Werniers, May & Szmalec, 2002).

This qualitative/quantitative distinction has also been employed in the Luck and Vogel (1997) change detection protocol. Thus in a *categorical change* context, an item in the array may change from a face stimulus at encoding to a cube stimulus in the test phase. In contrast, in a *within-category* change context, where high fidelity representation is required, a memory item such as a face may at test be another face, thus requiring high quality representation of the original face to be remembered (Scolari, Vogel, Awh, 2008). The use of such protocols has led to a debate about capacity in VSWM and the extent to which the need for high fidelity representation may constrain the number of integrated objects held within working memory (see Alvarez & Cavanagh, 2004; Awh, Barton & Vogel, 2007; Bays, Gatalo & Husain, 2009). However, for the purposes of the present chapter, it is interesting to note that this qualitative approach, assessing the high fidelity quality of visual memory, has been employed in a developmental context.

Figure 6 below indicates recent observations by Bull, Hamilton and Pearson (2007) which looked at developmental changes across two child age groups (5-8, 9-12) and an adult group in three tasks, the Size JND/Colour JND (collapsed score), VPT and Corsi task. The figure indicates a clear pattern of developmental fractionation, with significantly less age associated change in the JND task performance than in either the VPT or Corsi tasks. This suggests that in the younger children performance in this task is relatively mature. A recent study has further examined the quality of representation in children. Heyes, Zokaei, van der Staaij, Bays and Husain (2012) adopted their adult protocol for use with children. This study looked at changes in the precision of memory for orientations, with either 1 bar or 3 bar (sequential presentation) stimulus conditions. The procedure did not employ a change detection protocol, at retrieval a single probe identified the bar to match and participants employed a rotating dial to match the bar with the cued memory item orientation. The quality of representation was measured by identifying the discrepancy in orientation between the memory and rotated test item. This study revealed a number of interesting observations.

Precision of the representation increased from 9 to 13–years of age, both in the 1–item and 3-item conditions; however the 1-item fidelity was much greater than in the 3-item context (Heyes et al, Figure 2, p533). However, given that the 3-item condition involved sequential presentation, and a consideration of the issues in sequential presentation which were identified above, a qualification of the interpretation may be needed. However, the authors present the SPC data (Figure 3) and a strong single item recency effect is seen, much like the Hitch et al, (1988) and the Phillips and Christie, (1977), pattern of results. Thus, a collapsed 3-item figure perhaps obscures the more informative pattern. The authors interpreted their findings as support for a single resource model where the demands for high resolution demands will impinge upon the number of discrete chunks or objects which can be maintained within VSWM. One potential interpretation of the recency item effect in these studies is that the most recent item is under a highest level of activation within a narrow focus of attention able to maintain high resolution of the image, and the pre-recency items under a broader focus of attention where high fidelity cannot be maintained but still be higher than chance levels (Oberauer & Hein, 2011).

Hamilton (2011) has argued that tasks such as the Heyes et al. (2012) task which require high resolution, high fidelity representation, may require cognitive resources in the form of visual attention or *visualization* which are exogenous to working memory processes. He has argued, on the basis of recent research, that the maintenance of high fidelity representation is a consequence of top down visual attention processes acting on a derivative of perceptually driven activity in visual cortex (Berryhill, Chein & Olson, 2011; Gazzaley & Nobre, 2011; Serences, Ester, Vogel & Awh, 2009; Sergent, Ruff, Barbot, Driver & Rees, 2011; Todd, Han, Harrison, & Marois, 2011). As such, these high quality representations are unlikely to be supported by either visual or verbal LTM semantics, and thus have no (stable) place in the working memory workspace which is reserved for objects already bound and integrated by LTM interpretation (Cowan, 1988; Logie, 1995). Evidence from converging cognitive paradigms was employed to support this distinction. DVN impairs high fidelity representations (Dean, 2007; Dent, 2010; McConnell & Quinn, 2004) in the absence of an impact upon a conventional VSWM task, the VPT (Andrade et al., 2002; Hamilton, 2011). In addition, when allocation can be given to VPT maintenance, there is temporal stability, however even when allocation is allocated to representing high resolution information, the quality of the representation diminishes (Orme & Hamilton, submitted; Thompson et al, 2006).There are further implications with the use of these tasks within a developmental context.



Bull Hamilton and Pearson ESRC Figure 6

Figure 6. Developmental fractionation in quantitative measures of visuospatial working memory (VPT, Corsi) and collapsed qualitative measures of short term visual memory (Size/Colour JND).

Should the high fidelity representation be pre-categorical in nature, how does the development account of passive rehearsal followed by active refreshment relate to improvements in task performance (Camos & Barrouillet, 2011, Tam et al., 2010)? It is unlikely that any form of verbal embellishment and thus unlikely verbal rehearsal will underpin performance on these tasks, the nature of these tasks lend themselves to a visual (only) refreshment process. In addition, Heyes et al. (2012) noted a relationship between precision quality and intelligence task performance. This is in contrast to the adult findings reported by Fukuda, Vogel, Mayr and Awh (2010) where a categorical change, i.e. a quantitative measure, is more predictive of fluid intelligence measures. Thus, it may be the case that in a child research context, the attentional processes associated with visualization have more importance in the relationship with wider cognitive abilities.

CONCLUSION

It is clear in the content above that there is incongruence between the visuospatial material employed in a child developmental VSWM research context and the nature of the cognitive resources employed to respond to the task demands. In a task which involves the short term presentation of visuospatial material (on the surface), a complex and diverse range of cognitive resources may be employed, and their deployment and impact appear to be age associated.

Generic processes clearly exogenous to working memory such as processing speed, impact upon task performance in children, and age related improvements in processing speed may free up cognitive space (e.g. Case, 1982), minimise the decay of information in VSWM by allowing a quicker return to the re-activation of decaying traces (e.g. Towse et al., 1998), or allow greater opportunity for refreshment of the memoranda throughout the procedure (e.g. Barrouillet et al., 2004).

The application of verbal semantics and the increasing use of phonological resources in tasks demanding VSWM also develop through childhood, and this change in strategy may be seen as the hallmark characteristic of child development (Cowan & Alloway, 2008). One would presume that in parallel to the increasing strategic deployment of verbal semantics through childhood, a parallel improvement occurs with visual semantics; such a process would contribute to the enrichment of chunk representation, impacting directly on the compression process (Cowan et al., 2010). The increasing use of strategy and semantics is presumed to make demands upon attentional resources; these controlled processes may impact, during the encoding, maintenance, and retrieval phases of a VSWM task protocol.

Hamilton et al. (2003) argued that in order to disentangle these processes one may employ "...a task-analysis or componential-oriented approach." p66. This is clearly exemplified in the work of Cowan and colleagues (2010, 2011) where discrete attentional control processes at encoding and maintenance were controlled in order to identify developmental changes in the scope of attention or capacity of VSWM. Another way forward is to adopt a qualitative approach and consider visual short term memory for high quality representation, where the usefulness of visual and verbal semantics is necessarily constrained (Bull et al., 2007; Heyes et al., 2012).

However, should working memory in general, and more specifically visuospatial working memory function within the notion of a workspace where available functional architecture scaffolding is critical, then perhaps the *most* important question concerning child development should not address the development of specific cognitive resources, but more the increasing utilisation of the wider cognitive resources through childhood.

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