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## **Visuospatial Bootstrapping: When Visuospatial and Verbal Memory Work Together**

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## **Visuospatial Bootstrapping: When Visuospatial and Verbal Memory Work Together**

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Running Head: Visuospatial Bootstrapping

This manuscript refers to 31 references.

## **Abstract**

Visuospatial Bootstrapping is the name given to a phenomenon whereby performance on visually presented verbal serial recall tasks is better when stimuli are presented in a spatial array rather than a single location. However, the display used has to be a familiar one. This phenomenon implies communication between cognitive systems involved in storing short-term memory for verbal and visual information, alongside connections to and from knowledge held in long-term memory. Bootstrapping is a robust, replicable phenomenon that requires to be incorporated in theories of working memory and of how working memory interacts with long-term memory. This article provides an overview of bootstrapping, contextualises it within research on links between long-term knowledge and short-term memory, and addresses how it can help inform current working memory theory.

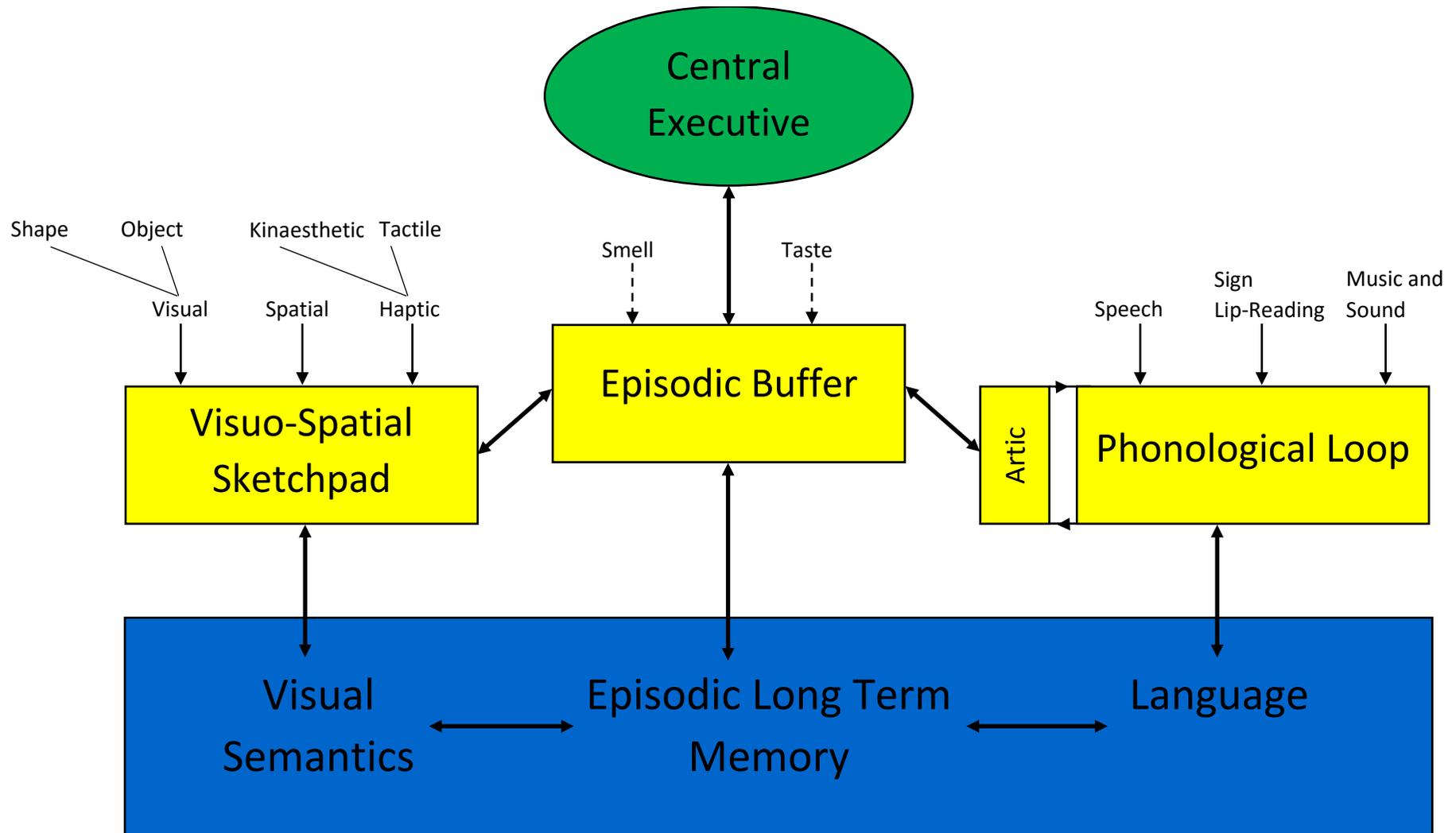
Key Words: Working Memory, Episodic Buffer, Long-term Memory, Short-term  
Memory

## **Visuospatial Bootstrapping: When Visuospatial and Verbal Memory Work Together**

People can remember details of specific events many decades after they happened. These memories can often be effortless and automatic, with the information being retained without conspicuous effort. However, there are also memory processes that can have different characteristics. These include ‘Working Memory’ processes, a term that simultaneously implies the effortful nature of the retention alongside the idea that information can be processed or worked upon. Cowan (2005) has suggested a model of working memory which proposes a key role for attention in activating the contents of memory for the purposes of processing and manipulation, describing it as the ‘few temporarily active thoughts’ (Cowan, 2010). Meanwhile Baddeley (2000; Baddeley, Allen & Hitch, 2011 – see Figure 1) argued for a dedicated ‘Central Executive’ which is called into operation when information requires to be processed or manipulated in memory.

Whilst Cowan’s approach emphasised activation of specific task-related material within long-term memory, Baddeley emphasised discrete short-term storage processes operating on information. Computation, manipulation and processing were separated from short-term storage, and held to be carried out by a set of executive or attentional processes. The processes of short-term storage were allocated to ‘slave systems’, in which information was subject to rehearsal.

There is evidence for the independence of visuospatial and verbal short-term memory (see Darling & Havelka, 2010 and Darling, Allen, Havelka, Campbell & Rattray, 2012 for reviews), and for independence of long and short-term memory (Baddeley, 2012). Nonetheless, there is evidence of long-term memory influence on short-term memory: ease of naming of abstract patterns facilitates their retention (Brown, Forbes & McConnell, 2006), and there is an enhanced short-term memory capacity for sentence-based word sequences



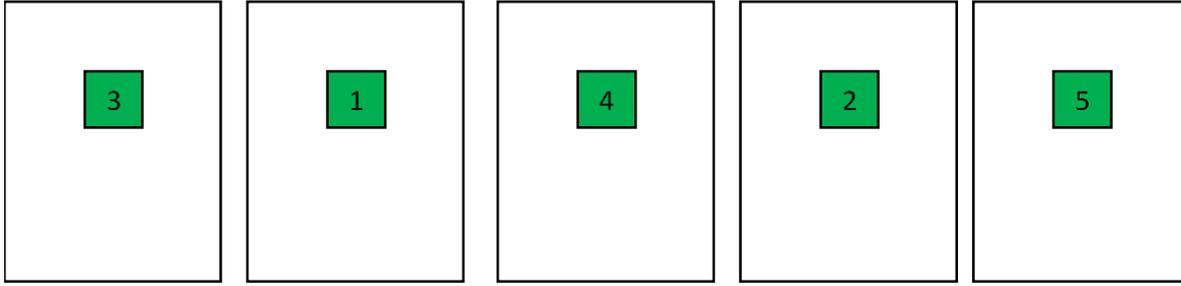
(Baddeley, Hitch & Allen, 2009). Observations of this sort led Baddeley (2000) to propose a new component for the working memory model - an 'episodic buffer'. Mnemonic processes mediating between short-term and long-term memory were within the remit of the episodic buffer, whilst processing and manipulation were thought to be within the remit of the central executive.

One class of tasks thought to recruit the episodic buffer are binding tasks – requiring the participant to recall the relationship between multiple aspects of a stimulus. For example, Morey (2009) asked participants to remember what a letter was and where that letter was in an array, demonstrating verbal-spatial binding. These bindings were susceptible to concurrent verbal interfering tasks, whilst spatial memory was not, implying that the verbal-spatial binding took place outside the spatial memory system. However, short-term memory binding tasks do not necessarily encapsulate the interaction with long-term knowledge that is a key feature of the episodic buffer.

### **Visuospatial Bootstrapping**

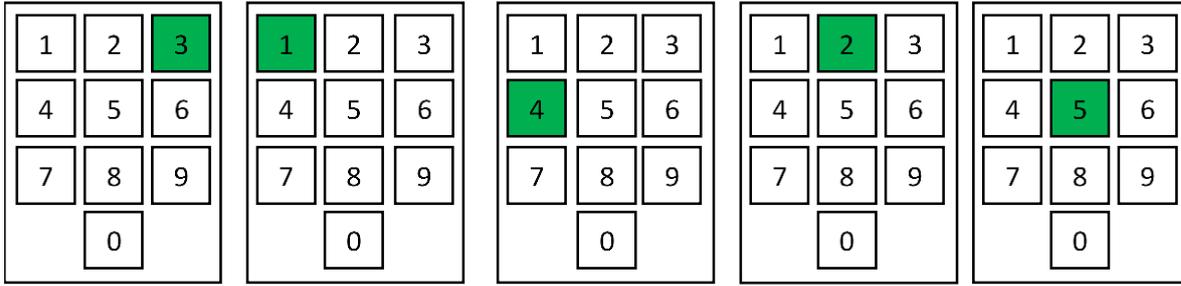
'Visuospatial bootstrapping' tasks were designed to address this possible shortcoming. In this task, participants verbally recall random digit sequences immediately after they have been presented on a computer screen. This kind of task is an archetypical short-term memory task. In an initial study, Darling and Havelka (2010) contrasted performance using three displays, a 'Control' condition, in which digits were presented sequentially in the middle of the screen, a 'Linear' condition in which digits were presented by highlighting them sequentially while they were displayed in a horizontal array across the screen and a 'Keypad' condition, similar to the linear array but based on the mobile phone 'T9' keypad (See Figure 2). Participants remembered more trials correctly in the Keypad condition than in either of the other conditions. The term 'visuospatial bootstrapping' was used to reflect the bootstrapping, or support, of verbal memory by visuospatial memory.

Control



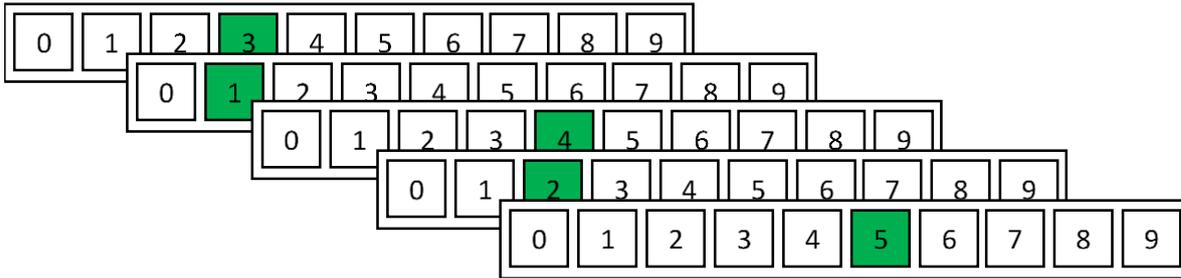
Recall

Typical



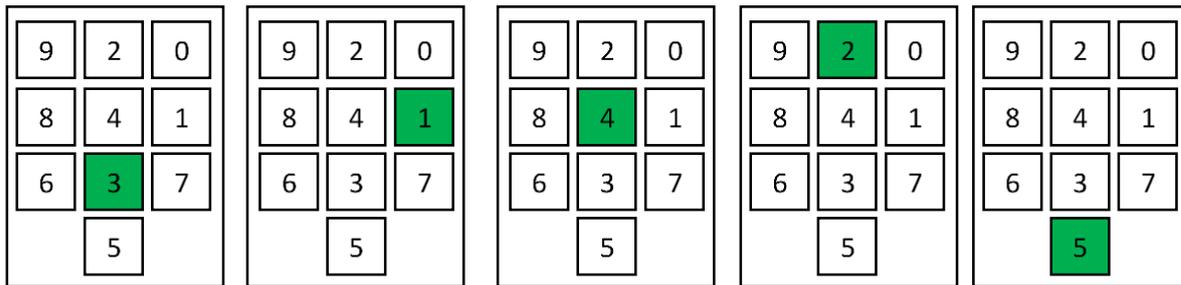
Recall

Linear



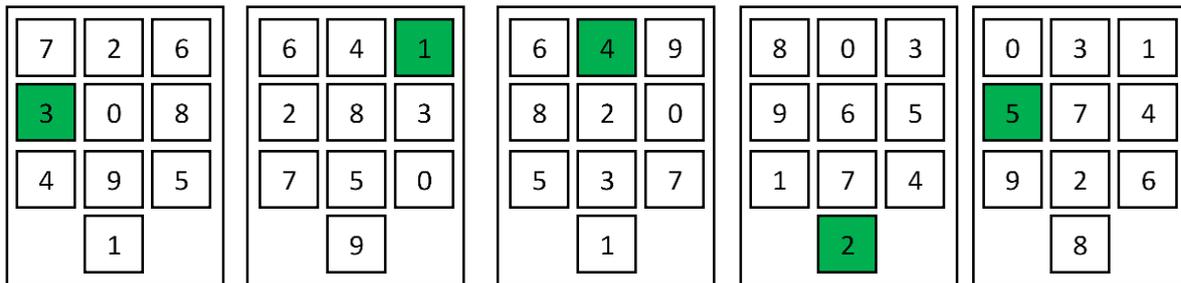
Recall

Random (Static Pattern)



Recall

Random (Dynamic Pattern)



Recall

Time

There is evidence from Parmentier and Andrés (2006) that recall of a sequence of locations in order is impaired when the path between them crosses itself many times, as would necessarily be the case in the linear array. This could potentially account for the lack of a bootstrapping effect on linear arrays. Darling et al. (2012) sought to replicate the bootstrapping effect using arrays where this issue could not confound recall. Alongside the original Control and Keypad conditions, two new random keypad conditions were added in this study (see Figure 2). These had the same shape as the Typical Keypad, but the digits were mapped randomly to locations. Only the Typical Keypad display was associated with improved memory performance. This pattern suggests participants accessed knowledge of the keypad display held in long-term memory, otherwise performance should also have been enhanced in the Random Keypad conditions. Lack of facilitation in the Random Keypad condition also excludes the possibility that the apparent improvement in the Typical Keypad condition resulted from interference caused by repeating digits in one location. Consequently, bootstrapping was argued to be supported by linkages between verbal short-term memory (the ‘phonological loop’ slave system of the working memory model) and long-term visuospatial knowledge.

Articulatory suppression, the continuous repetition of a syllable or phrase, is an effective inhibitor of activity in the phonological loop (Baddeley, 2000). When carried out during encoding in a bootstrapping task it has been seen to decrease memory performance in both Control and Keypad display conditions (Allen, Havelka, Falcon, Evans and Darling, 2015). However, the impact of articulatory suppression was greater in the Control than in the Keypad condition, and the positive impact of providing extra visuospatial information was greater when the verbal short-term memory system was under heavy load by articulatory suppression. Visuospatial systems potentially provided additional support to verbal short-term memory when it was challenged, and bootstrapping was not eliminated even when

phonological loop efficiency was compromised; consequently, it must have relied on processes beyond the phonological loop.

A second experiment in the paper by Allen et al (2015) attempted to inhibit spatial encoding by using requiring participants to touch a sequence of locations in a predetermined order, a task which is known to impair spatial rehearsal processes (Logie, 2003). This task completely eliminated the Keypad condition benefit, indicating the involvement of spatial short-term memory (the 'Visuo-Spatial Sketch Pad' slave system) in bootstrapping. The role of spatial short-term memory was specific to encoding, because a third experiment showed that tapping at recall did not abolish the bootstrapping effect, ruling out the possibility that participants maintained separate memory traces and then combined them using long-term memory knowledge at recall. In sum, the bootstrapping effect seems to suggest the storage of a multimodal representation linking traces in separate verbal and visual short-term stores with information in long-term memory. Any system enabling this would be resemble the Episodic Buffer (Baddeley, 2000, 2012; Baddeley et al, 2011), and would also be consistent with results from Langerock, Vergauwe & Barrouillet (2014) who concluded that the capacity limit for cross-domain verbal-spatial bindings was lower than the capacity limit for unbound features and that domain-specific resources were not involved in the maintenance of the cross-domain bindings.

There are reasons to predict that bootstrapping is independent of executive attention: firstly, increasing evidence that episodic buffer binding processes are independent of attention (Baddeley et al., 2011; Langerock et al, 2014); secondly, the fact that verbal-visuospatial binding in bootstrapping is incidental to task instructions implies a degree of automaticity. Finally, bootstrapping seems to be suited to implementation in a storage focused component such as a buffer, being a short-term storage task, quite different from the processing oriented working memory span tasks used extensively to understand general

functioning of working memory from a psychometric perspective (e.g. Daneman & Carpenter, 1980; Engle & Kane, 2004).

Calia, Darling, Allen & Havelka (2015) found that similar bootstrapping effects were observed in younger (19-35 years) and older (55-76) adults with no evidence of an interaction between age and display type, once the decline in overall verbal span was adjusted for. There is evidence (see Park & Reuter-Lorenz, 2009) that older adults' executive function is less effective than younger adults, so the persistence of a largely equivalent bootstrapping effect in older adults supports the claim that bootstrapping does not weigh heavily on attentional or executive resources. Incidentally, Darling, Parker, Goodall, Havelka and Allen (2014) identified that children of age 9 showed evidence of bootstrapping, so it seems likely that bootstrapping, consistent with a mature episodic buffer, is present from at least age 9 across the lifespan.

Visuospatial bootstrapping was also preserved in a group of patients with medial temporal lobe amnesia (Race, Palombo, Cadden, Burke & Verfaellie, 2015) who showed severe difficulties with learning new material. These amnesic patients showed a bootstrapping benefit. They also showed increased word recall when presented in a sentence context (a 'sentence superiority effect'), previously argued to index episodic buffer function in the verbal domain (e.g. Baddeley et al., 2009). These data clearly indicate short-to-long-term memory links, consistent with the episodic buffer, that are preserved in the case of hippocampal damage. It is worth noting, too, that this study independently replicated bootstrapping in healthy older adult controls.

Bootstrapping is one of a number of tasks that incorporate an element of 'leveraging stored semantic knowledge to improve memory performance' (Race, et al., 2015, p.272). Further examples of this include sentence superiority (Baddeley, et al., 2009), familiarity within digit sequences (Jones and Macken, 2015), and expert memory effects in chess (Chase

and Simon, 1973), music (Sloboda, 1976) and abacus use (Hatano & Osawa, 1983). We also note work by Smith & Jarrold (2014) who showed that presenting pictorial representations of words alongside verbal presentations facilitated memory performance in typically developing children and children with Down Syndrome. Compared to these other long-term memory leveraging tasks, bootstrapping invokes a more definitively spatial form of visuospatial processing, related explicitly to location. Furthermore, its key features have been systematically evaluated and are now well understood, enabling confidence in the claim that bootstrapping emerges from an Episodic Buffer like pattern of links between verbal short-term memory, visuospatial short-term memory, and long-term knowledge that are probably quite automatic in nature.

Some authors (Quak, London & Talsma, 2015) have argued that it makes sense to adopt a multisensory perspective of working memory. Meanwhile, influential approaches to working memory such as the Embedded Processes model (Cowan, 2005) and psychometric approaches (Engle & Kane, 2004) do not explicitly invoke dedicated modality specific storage systems. Exploration of the bootstrapping phenomenon might illuminate this issue. Firstly: it is likely that processes linking multimodal long and short-term memory that support bootstrapping are likely to lie below the level of attention and executive processing (Calia et al., 2015). Secondly loading the individual modality-specific components of working memory with interfering tasks causes the effect to break down in a predictable way, consistent with modality specificity (Allen, et al., 2015). Based on this, it would be premature to dispense with modality specificity yet. Beyond this particular issue, though, the visuospatial bootstrapping phenomenon has useful and novel implications for a range of WM models, and theorists developing such models should consider how to incorporate these findings.

## **Future Directions and Applications**

It is also worth briefly speculating about processing in the episodic buffer. Our bootstrapping data suggest a process which interacts with long-term knowledge to enable contextual integration across multiple independent stimulus modalities. Superficially, this may not seem very episodic in nature – certainly any one participant in a bootstrapping study may see upwards of 200 individual digits presented, and seems quite unlikely to be encoding those individual episodes for future mental time travel (Tulving, 2002). Consider, though, that the episodic significance of a collection of individual co-occurring stimuli may only be apparent sometime after an event, therefore the systems that are necessary for the laying down of an episodic trace may not actually need to initially code those items as an episode. However, they do need to be temporarily coagulated, into a unit which has the potential for later encoding. Perhaps the role of the episodic buffer is to maintain constellations of stimulus attributes from across the range of short-term memory systems, to allow potential encoding by long-term memory systems depending on biological, situational or processing needs. Bootstrapping results suggest that spatial information is perhaps particularly important in this kind of process, an assertion that is bolstered by recent work (van Dijck & Fias, 2011, Guida & Lavielle-Guida, 2014) asserting the importance of spatial information in order recall.

This speculation generates testable predictions. Firstly, while its potential automaticity makes it difficult to disrupt the functioning of the episodic buffer independently of disrupting the modality specific systems, two long-term memory leveraging tasks that ostensibly overlap little (such as sentence context and item-location binding) should mutually disrupt each other. Secondly, overloading episodic buffer in this way might inhibit the formation of episodic traces in long-term memory. Finally, one might expect implicit

bindings involving long-term memory (like bootstrapping) to be fairly short-lived in most situations.

It is not desirable for theoretical research to proceed in a vacuum, and the working memory model has a history of enabling considerable clinical advances to be made (e.g. Foley, et al. 2011; Gathercole & Alloway, 2008). However, as yet, the episodic buffer hypothesis has been somewhat slow in deriving applications. One key issue is that it has been difficult for researchers and clinicians to understand how the episodic buffer could be assessed in a practical way. The bootstrapping task is a potentially informative tool to achieve this. It would be simple to adapt the experimental tasks into a useful clinical and research tool that could be administered in minutes. Development of such a test awaits targeted research, but given the resilience of the bootstrapping phenomenon to ageing (Calia et al., 2015) and amnesia (Race et al., 2015) this would be a promising avenue to follow.

## Notes

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## Figure Captions

Figure 1. The working memory model. The figure shows how two slave systems handling various subtypes of modality specific information (Phonological Loop and Visuo-Spatial Sketch Pad) interact with a multimodal channel, the Episodic Buffer. These short-term storage components are subject to influence by processes within the Central Executive, but can also be influenced by information in long-term memory. This diagram is our own attempt to combine the ideas presented by Baddeley (2000), in which the interactions of long-term memory and fluid structures of working memory were highlighted, with those of Baddeley et al. (2011), which modified the relationship between the Central Executive and the Episodic Buffer as well as expanding how different stimulus subtypes may be accommodated within the model.

Figure 2. A diagrammatic representation of the visuospatial bootstrapping task, showing five types of stimulus. In all conditions digits are presented visually at a rate of around one per second, for verbal recall when the 'recall' message is shown. The extra visuospatial information in the Typical condition facilitates performance compared to the Control condition, and this is what is referred to as 'bootstrapping'. The linear condition was used in the study by Darling & Havelka (2010) and was not associated with better recall. The two random conditions have been used in some studies (Darling et al., 2012; Darling et al., 2014; Calia et al., 2015; Race et al., 2015) and have never produced improved recall.

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## **Recommended Readings**

Allen, R.J., Havelka, J., Falcon, T., Evans, S. and Darling, S. (2015). (See References). A study which presents the bootstrapping methodology and uses interference tasks to identify the locus of processes underlying the effect.

Baddeley, A.D. (2012). (See References). A comprehensive overview of the development and the current understanding of the Working Memory model.

Cowan, N. (2010). (See References). An alternative and influential model of working memory.

Langerock, N., Vergauwe, E. and Barrouillet, P. (2014). (See References). An article that provides evidence for cross-domain binding of verbal and spatial information at encoding and without attentional demands, and hence a similar pattern of observations to the bootstrapping work, but using a different method and within the context of a different theory of working memory

Race, E., Palombo, D.J., Cadden, M., Burke, K. and Verfaellie, M. (2015) (See References). Evidence of preserved visuospatial bootstrapping and other long-term memory effects in short-term recall in patients with hippocampal damage. Contains a replication of bootstrapping independent of the authors of other bootstrapping studies.