Visuospatial bootstrapping

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Visuospatial bootstrapping: binding useful visuospatial information during verbal working memory encoding does not require set-shifting executive resources.

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Abstract

Immediate serial recall of digits is better when the digits are shown by highlighting them in a familiar array, such as a phone keypad, compared to presenting them serially in a single location; a pattern referred to as 'visuospatial bootstrapping'. This pattern implies the establishment of temporary links between verbal and spatial working memory, alongside access to information in long term memory. However, the role of working memory control processes like those implied by the 'Central Executive' in bootstrapping has not been directly investigated. Here we report a study addressing this issue, focusing on executive processes of attentional shifting. Tasks in which information has to be sequenced are thought to be heavily dependent on shifting. Memory for digits presented in keypads versus single locations was assessed under two secondary task load conditions, one with and one without a sequencing requirement, and hence differing in the degree to which they invoke shifting. Results provided clear evidence that multimodal binding (visuospatial bootstrapping) can operate independently of this form of executive control process.

Keywords: Working memory; Central Executive; Visuospatial Bootstrapping, executive function, Attentional shifting.

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Visuospatial bootstrapping: binding useful visuospatial information during verbal working memory encoding does not require set-shifting executive resources.

Segregation of verbal and visuospatial short term or working memory systems has been a key aspect of modality-specific models of working memory (e.g. Baddeley, 2000; Baddeley, Allen, & Hitch, 2011; Logie, 2011) in which verbal processes are carried out within a 'phonological loop', whilst visuospatial processes are accommodated within a 'visual spatial sketch pad'. Other influential models of working memory including embedded processes (Cowan, 2005, Oberauer, 2009), time based resource sharing (Barouillet & Camos, 2010) and limitless capacity (Macken, Taylor & Jones, 2015) place less emphasis on the modality specificity of discrete subcomponents, but nonetheless still accommodate empirical data indicating simultaneous encoding of stimulus attributes in different modalities (e.g. visual and verbal: Morey, 2009; Logie, Della Sala, Wynn & Baddeley, 2000; Logie, Saito, Morita, Varma and Norris, 2016).

Under the hypothesis of modality specificity in working memory, tasks where verbal and visuospatial stimulus elements are retained together (e.g. Morey, 2009) require simultaneous encoding in both visuospatial and verbal working memory systems, and a way of linking them together. To address this issue within the multicomponent model, Baddeley (2000) added the 'episodic buffer'. This is proposed as a limited capacity store, recruited when information from different sources is bound together and retained in working memory (e.g. Allen, Baddeley, & Hitch, 2006; Allen, Hitch, & Baddeley, 2009; Baddeley, Hitch, & Allen, 2009; Bao, Li & Zhang, 2007; Karlsen, Allen, Baddeley, & Hitch, 2010). Although initially thought to require active engagement of the central executive (Baddeley, 2000), there is now evidence indicating that the creation of bound representations and their possible registry in

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the episodic buffer is a relatively automatic process (Langerock, Vergauwe & Barrouillet, 2014; Allen, Baddeley, & Hitch, 2014; Allen, Hitch, Mate, & Baddeley, 2012).

‘Visuospatial Bootstrapping’ (for a review and discussion see Darling, Allen & Havelka, 2017) describes the observation that when asked to carry out serial recall of digits previously presented on a computer screen, participants perform better if numbers are shown by sequentially highlighting them within a depiction of the familiar ‘T9’ phone keypad, compared to control conditions. The pattern is named for the fact that visuospatial processes appear able to boost – bootstrap – verbal recall performance when incidental visuospatial information is available at encoding. Bootstrapping benefits considerably from familiarity of the participant with the keypad display being used, leading to the conclusion that it typically involves a long-term memory component (Darling, Allen, Havelka, Campbell & Rattray, 2012), though there is now evidence that some spatial support to verbal memory is possible without a connection to long term knowledge (Allan, Morey, Darling, Allen & Havelka, 2017). Allen, Havelka, Falcon, Evans and Darling (2015) administered tasks aimed at causing verbal and spatial suppression during presentation of digits and found that bootstrapping persisted under suppression of verbal working memory but was completely abolished under spatial load during encoding (though not recall), demonstrating that bootstrapping recruited spatial working memory resources but did not recruit verbal resources beyond those used in the single item condition, and that these resources were recruited during encoding. [1]

Whilst previous research on bootstrapping has focused on short-term storage, the notion of working memory implies both storage and manipulation of information. The manipulation of

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[1] Note that visuospatial working memory processes may include or overlap with motor planning processes (e.g. Smyth & Scholey, 1994) – and hence that visuospatial bootstrapping may invoke processes used in motor function. It is possible that one reason for the effectiveness of the T9 keypad in bootstrapping tasks comes from its strong association with motor outputs.

information during temporary retention has been proposed to be the responsibility of the Central Executive (Baddeley and Hitch, 1974; Baddeley, 2000; Cowan, 2005), a label that intentionally links the management and manipulation of information in working memory with the idea of executive function. Executive functions are those that ‘modulate the operation of various cognitive subprocesses and thereby regulate the dynamics of human cognition’ (Miyake, Friedman, Emerson, Witzki and Howerter, 2000, p50) and are considered to be a key feature of models seeking to understand working memory (Baddeley, 2012, 2007; Cowan, 2005; Oberauer, 2009; Barouillet & Camos, 2010). The term is a general label applicable to processes that are similar in that they sit at an organisational or attentional level which is superordinate to other cognitive systems, but that have distinct, potentially interactive functions. Such a conception implies both similarity and heterogeneity within putative executive processes. Individual differences approaches have consistently identified a tension between unity and diversity of executive function (e.g. Teuber, 1972; Duncan, Johnson, Swales & Freer, 1997; Miyake, Friedman, Emerson, Witzki and Howerter, 2000). Miyake and Friedman (2012) argue that executive functions encompass diversity in the form of specific shifting and updating processes, alongside unity, represented by a common set of underlying processes labelled (‘Common EF’), and that tasks which involve executive functions might recruit specific shifting and/or updating functions alongside Common EF processes. Shifting reflects the process of alternating between different ongoing processes or mental sets – and is often otherwise known as ‘attention switching’ or ‘task switching’. Updating involves monitoring and rapid editing of working memory contents. Common EF is thought to involve active maintenance of task goals and goal-related information and the potential to control lower-level processing in the pursuit of such goals. It is also thought to underlie inhibition (Miyake and Friedman, 2012).

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So far there is no evidence one way or another as to whether bootstrapping – the specific advantage to memory of recalling verbal material that is presented in a familiar spatial array – has an executive dimension. One possibility is that the effect is consequent upon conscious strategic processing – participants assess the problem and identify explicitly that retaining a spatial sequence will assist performance. Such an approach would likely load the gamut of executive functions. Another possibility is that the visuospatial processing in the bootstrapping effect (Allen et al, 2015) may invoke some executive demand: whilst verbal serial recall tasks are generally considered to have relatively minimal executive demand (see e.g. Engle, Tuholski, Laughlin & Conway, 1999), there is evidence that visuospatial tasks may have a somewhat higher executive load (Miyake, Friedman, Rettinger, Shah & Hegarty, 2001). Despite this, there are some reasons to suspect that the bootstrapping effect may *not* be the product of executive functioning. Some kinds of binding between items in working memory seem independent of executive function (Baddeley et al, 2011; Langerock et al, 2014 – though the picture is not clear-cut (see e.g. Elsley & Parmentier, 2009; Gao, Wu, Qiu, He, Yang, & Shen, 2017; Peterson & Naveh-Benjamin, 2017), which likely reflects the range of executive functions assessed in different studies and serves to justify the approach taken here of focusing on discrete executive functions. Additionally, evidence that bootstrapping is not affected by cognitive ageing (Calia, Darling, Allen & Havelka, 2015) can be interpreted to suggest that bootstrapping may be relatively less reliant on executive function.

The present study set out to assess the contribution of executive functions supporting shifting to bootstrapping by using a dual task approach, seeking to observe the impact of carrying out an executively demanding task during the encoding phase of the bootstrapping paradigm. The study of Allen et al (2015) assessed the effects of loading the verbal and visuospatial slave systems proposed in the multi component model (Baddeley et al, 2011) on bootstrapping, whilst here we sought to investigate the effect of loading set-shifting, a potential executive function and hence role of the Central Executive (Baddeley, 2012) on the same phenomenon. We compared two conditions in which participants took part in a visually-presented serial digit recall task. In one condition the digits were presented one after another in the middle of the screen, whilst in the other they were presented by highlighting the to-be-remembered sequence one-by-one against a keypad display. In both display conditions, participants were asked to recall the sequence verbally, and the only difference between conditions was the way the material was displayed. If a bootstrapping effect were present, keypad displays would show superior performance, facilitated by the additional opportunity afforded by the display for participants to bind spatial-sequential information with LTM knowledge about the keypad array and the verbal material.

Single item presentations and keypad presentations do differ on a number of axes but previous research has indicated that fully controlling for these does not change the bootstrapping effect – strong benefits to verbal memory have consistently been seen when comparing a familiar T9 keypad array to random keypad arrays (Darling et al, 2012; Darling, Parker, Goodall, Havelka & Allen, 2014; Calia et al, 2015, Allan, et al, in press; Race, Palombo, Cadden, Burke & Verfaellie, 2015). Consequently, we adopted single item presentations as the baseline in this study to maintain maximal consistency with previous studies, the majority of which have included a single item condition.

In order to load executive functions with emphasis on elements related to shifting, we adopted two different load conditions originally implemented in a study of sequencing in

arithmetic switching (Baddeley, Chincotta & Adlam, 2001). Both secondary tasks required participants to carry out articulatory suppression during encoding. However, in one case the suppression was simply an overlearned sequence (days of the week or months of the year) whereas in the other case the day and month responses had to be alternated, forcing participants to sequence the same material in novel and unfamiliar ways. A very similar task is known to impair random key pressing, itself known to be sensitive to executive function (Baddeley, Emslie, Kolodny & Duncan, 1998). Sequencing days and months invokes shifting (switching between the two lists), and indeed the task was originally designed to be used to load attentional shifting. It is also likely to load on inhibition (inhibiting the immediate prepotent response, e.g. saying 'February' after 'January'). Sequencing also loads executive function under Norman and Shallice's (1986) Supervisory Attentional System model, given that automatic schemata for the alternating lists would be unlikely to exist prior to the experiment. Baddeley (2007)
and Cowan (2005) both argue that switching attention is one of the principal roles of the central executive in their respective theoretical models. Oberauer (2009) distinguishes between declarative and procedural working memory, where the former is responsible for maintaining representations and the latter is responsible for processing or manipulating those representations. Accessing an overlearned sequence (i.e. days of the week, or months of the year) minimises demands on procedural elements like controlled retrieval, switching and response selection. Consequently, comparing the tasks allows assessment of the insertion of an executive load based on shifting.

If participants showed intact bootstrapping effects whilst undertaking the sequencing task, this would imply the independence of multimodal binding from executive processes linked to shifting. Alternatively, if bootstrapping is reliant on shifting, we would expect to see its attenuation under increased executive load, as the control processes supporting the sequencing task would block the control processes enabling the encoding of verbal—visuospatial representations in the keypad condition.

Method

Design

A 2x2 repeated measures design was implemented, manipulating display type (single item vs. keypad) and concurrent task (days/months [i.e. articulatory suppression alone] vs. day-month sequencing [i.e. articulatory suppression + sequencing]). Two dependent variables were recorded for consistency with measures reported in previous bootstrapping work. These were (1) total correct trials (/20: TCT), i.e. the number of trials in which all items were correctly recalled in the correct order and (2) proportion digits correctly recalled (PDCR), i.e. the mean proportion of digits which were correctly recalled in the correct sequence position per trial (PDCR). The hypotheses applied equally to both measures. Trials were blocked by condition and fully counterbalanced.

In the main experimental blocks, participants received digit sequences that were two items smaller than their own span, which was assessed in an initial pre-test. This change in method from previous studies in which participants had been tested at their measured span (Darling, Parker, Goodall, Havelka & Allen, 2014; Allen et al, 2015; Calia et al, 2015) was necessitated by piloting showing floor performance under the day-month sequencing secondary task. The procedure took no longer than 1 hour, and the research was approved by the Research Ethics Committee at Queen Margaret University.

Participants

There were 48 participants (9 males, 39 females; median age: 26.10 years, SD = 6.48, range 19 to 41). All were students or staff members at Queen Margaret University and native English speakers. Participants gave informed consent. We set the stopping rule to 48 on an *a priori* basis for two reasons – firstly, previous research on bootstrapping using similar designs had typically used sample sizes of N=32 or N=48 (e.g. Darling, et al, 2012; Allen et al, 2015; Calia et al, 2015) and secondly to allow 2 participants to contribute to each of the 24 combinations of task order.

Materials and Procedure

A laptop PC with a 15 inch (38 cm) display was used to present the stimuli, which were compiled using e-prime 2 (Psychology Software Tools, 2013). Digit presentation began with the presentation of a central fixation cross for 1000ms. The digit sequence was then shown. Each digit in the sequence was visible for 1500ms. Digits were presented in black 48 point Arial font within black square outlines measuring 120 x 120 pixels (see Figure 1). The screen background was white. There were 250ms blank screen intervals between digits. For the single item display, each number was presented in isolation at the centre of the screen, with a green background to its square. For the keypad display, all of the digits from 0 to 9 were presented within their squares and were visible within the T9 keypad layout, with 10 pixels separating each square. The to be remembered digit was identifiable by having a green background to its square, all the other digits were visible in their squares but had an unfilled (i.e. white) background . After the final digit, there was a retention interval of 1000ms, following which the message "Repeat" was presented in the middle of the screen and participants attempted to verbally recall the sequence of digits in the correct order, without a time limit. The experimenter pressed a button to initiate each new trial after the response from the participant was completed.

Sessions started with a span test (using the single item display condition with no secondary task) in order to ascertain sequence length to use for each participant. An increasing span procedure was used with length progressively incremented in steps of one from a single item upwards, with two sequences at each length. Testing continued until participants failed to correctly recall both sequences, with span classed as the maximum length at which at least one sequence was accurately recalled. The four condition specific blocks then followed, with each containing 20 test trials performed at the same difficulty level, which was set at the obtained span minus 2.

In both secondary task conditions participants vocalised days of the week and/or the months of the year. Vocalisation was performed from fixation to the start of recall. A message preceded each trial for 3000ms. In the days/months condition, participants were instructed to repeat either the days of the week or the months of the year starting from a specified day or month (e.g. "Please say the days of the week in order starting with a Tuesday"). In the day-month sequencing condition participants were told to continually intermix the day sequence with the month sequence (e.g. "Please say the days of the week starting with Wednesday and the months of the year beginning with June" – a sample response would be, *Tuesday, July, Wednesday, August,* etc.). Prior to the trials, the experimenter explained the sequencing task by giving an example. The requirement to say days or months in the days/months condition and starting items in both conditions were randomised.

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Results

Participants achieved a mean span score of 6.47 (SD = .74: Max = 8, Min = 5) in the pre-test, hence mean span tested in the experimental blocks was 4.47.

Figure 2 shows the total number of trials correctly recalled in the different conditions of the study (i.e. the TCT dependent variable). We entered these values into a Bayesian ANOVA with display (single item, keypad) and secondary task (days/months, day-month sequencing) as fixed factors and participant ID as a random factor (using the BayesFactor package in *R*: see Rouder, Morey, Verhagen, Swagman & Wagenmakers, 2016). The default prior range setting was used in which 50% of true effect sizes are within ±0.707. The best model (BF_{10}=7.77x10^{34}, ± 1.67%) included main effects of both factors but no interaction. Although inclusion of display (BF_{10} = 3.53x10^{11}± 5.89%) and secondary task (BF_{10} = 5.35x10^{13}± 0.88%) were each *extremely*[2] indicated over a model including no effects, the model including both main effects was itself *extremely* preferred (vs. display BF_{10} = 1.45x10^{21}± 1.89%: vs. secondary task BF_{10} 2.20x10^{23}± 6.12%)). Evidence against the interaction was inconclusive (BF_{10} = 0.62. ± 3.68%). This pattern indicated superior recall for digits in the keypad condition relative to single item displays, i.e. a bootstrapping effect, and inferior recall when the sequencing requirement was added to articulatory suppression. The main effects of display task and secondary task were considerable (Cohen's *d*s = 1.66 and 1.89 respectively). The interaction effect was more moderate (η_p^2=0.06, Cohen's *d* equivalent = 0.52). This interaction was a fairly unlikely contributor to explaining the data, and note that

--- Insert Figure 1 about here ---

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[2] Interpretative descriptors for Bayes factors presented in italics are taken from Lee and Wagenmakers' (2013) adaptation of Jeffreys' (1961) work.

the means showed a slightly *larger* benefit for keypad displays in the day-month sequencing condition than in the days/months condition.

Figure 3 reports mean proportion of digits recalled correctly in position per trial across the experimental manipulations (i.e. the PDCR dependent variable). These were also analysed using a Bayesian ANOVA with a similar approach to the previous analysis. The best model (BF_{10}=4.94x10^{32}, ± 2.93%) included main effects of both factors and the interaction between them. Although inclusion of display (BF_{10} = 6.39x10^{10}± 5.26%) and secondary task (BF_{10} = 1.32x10^{13}± 1.01%) were each *extremely* indicated over a model including no effects, the model including both main effects was itself *extremely* preferred (vs. display BF_{10} = 1.73x10^{21}± 7.55%: vs. secondary task BF_{10} 8.34x10^{18}± 5.50%)). The additional inclusion of the interaction was *moderately* favoured (BF_{10} = 4.48, ± 6.15%). Hence there was evidence of a substantial benefit for keypad displays and a substantial performance cost of adding sequencing, and additionally, the size of the bootstrapping effect increased when sequencing was added to the secondary task. The main effects of display task and secondary task were considerable (Cohen's *d*s = 1.60 for both). The interaction effect was smaller but still substantive (η_p^2=0.21, Cohen's *d* equivalent = 1.02).

To check whether there was a trade-off in performance between the secondary task and the serial verbal memory primary task we analysed recordings of vocalisations during the secondary task, coding mean number of utterances (i.e. vocalisations of months or days) per trial and mean number of errors (incorrectly sequenced months or days) per trial. There was a failure in audio recording for 6 participants so the sample for these analyses was N = 42. Because error rates were low (only 1.11% of utterances were out of sequence) , a simple

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performance score indexing the number of correct items produced (i.e. utterances – errors) was derived and analysed to see if secondary task performance was impacted by the experimental manipulations. The best model of these data (BF_{10}=7.35x10^{16}, ± 0.75%) included only interference (performance was worse when sequencing was added: days/months /*X* = 16.93, *SD* = 5.92; day-month sequencing /*X* = 10.88, *SD* = 14.66; *d* = 1.47), and this model was *moderately* favoured over the model including interference and display (vs. interference and display: BF_{10}= 3.83 ± 2.96%) and this model itself was in turn *moderately* favoured over the model including the interference x display interaction (vs. interaction: (BF_{10}=3.15, ± 13.43%). This evidence against the interaction is evidence against the possibility that performance of bootstrapping on the memory task was traded off against performance on the day-month or sequencing tasks.

Data Availability

The data associated with this research are available online at http://osf.io/9k4qe

Discussion

Performance in the keypad condition was consistently higher than in the single item condition—this is what we refer to as the bootstrapping effect. There was also a decrease in overall memory performance when a requirement to carry out sequencing was added to the articulatory suppression task, demonstrating that the sequencing task impaired verbal immediate serial recall, and hence that it used some of the same resources. As the memory demands of the two interference tasks were similar, the locus of this conflict was likely outside verbal short term memory. Critically, executive sequencing load did *not* attenuate the positive effects of viewing keypad displays: indeed, the benefit of keypad displays increased under executive load on the PDCR dependent variable. It can therefore be concluded that

--- Insert Figure 2 about here ---

--- Insert Figure 3 about here ---

bootstrapping at encoding is independent of the executive resources taxed by the sequencing task in this experiment and that bootstrapping and sequencing likely rely on separate cognitive architecture. Baddeley et al (2001) demonstrated that the sequencing task used in the present study effectively targets shifting, one of Miyake & Friedman's (2012) two specific 'diverse' executive functions. Hence, executive shifting ('task switching' or 'attention switching') between mental sets is a function that is separate from the processes supporting bootstrapping.

Miyake and Friedman (2012) suggest that switching tasks recruit a combination of a specific shifting function and Common EF, and we might speculate that some of the inhibitory processes related to suppressing the prepotent response of saying, for example, 'February' after 'January' instead of the required 'Tuesday') may relate to inhibition and hence to Common EF (as variance attributable to inhibition is completely subsumed by CommonEF) . If this is accepted, then present results suggest that bootstrapping may also be independent of some of the more 'united' executive functions represented within Common EF. It is perhaps unlikely that insertion of sequencing to articulatory suppression in the sequencing task here would increase its updating requirements, given that updating is thought to reflect active manipulation in working memory, and because of this it is also hard to draw conclusions about bootstrapping and updating. One might expect them to be independent, though: whilst digit recall tasks probably involve updating, it is hard to envisage how updating relates specifically to the advantage bestowed by keypad presentations. Nonetheless, returning to this study's principal focus on shifting: these results do unequivocally demonstrate

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independence of bootstrapping from a definable and segregable subset of shifting-specific executive processes.

It is conceivable that bootstrapping relies on explicit, conscious, strategic processes that are optionally available to participants, but this is unlikely given evidence that bootstrapping *increased* on the PDCR variable during the complex sequencing task. Instead, bootstrapping is probably automatic and efficient. This is consistent with recent speculation based jointly on related binding research (Darling et al, 2017), and on the observation that aging does not attenuate bootstrapping (Calia et al, 2015). It is also consistent with the fact that bootstrapping emerges without any explicit instruction on the part of the experimenter.

An alternative explanation for the bootstrapping pattern is possible – instead of representing a connection between visuospatial and verbal information during *encoding*, it is possible that in the single item condition, *verbal* information is of key importance, whilst in the typical, familiar keypad condition the key information being retained is *visuospatial.* Under this explanation, the bootstrapping effect is established at recall, where processes link the short-term visuospatial memory trace with the known digit locations, producing superior recall. This explanation is potentially consistent with results from random keypads (where visuospatial bootstrapping is not seen, e.g. Darling et al, 2012), as random keypads would exact an additional verbal short-term memory load in retaining the novel digit-location mappings. However, two features of the data from the study by Allen et al (2015) tend to contradict this possibility. Firstly, verbal load (articulatory suppression) had an overall effect on performance in the typical keypad conditions – in other words, even though the proportion of performance attributable to bootstrapping (i.e. the typical – single item difference) was *increased* when verbal memory was loaded, overall performance (i.e. the mean number of items recalled in both conditions) was still impacted by the verbal load imposed by articulatory suppression. Verbal memory was thus clearly implicated at some level in the encoding of the material, and it is evidently *not* the case that locations alone need be maintained to allow maximal performance in the typical keypad condition. Secondly, evidence from Experiment 3 of Allen et al (2015) shows that when visuospatial load was applied during retrieval, bootstrapping was not eliminated. This is evidence that the role of visuospatial working memory in bootstrapping is complete before retrieval; given this it is implausible that the digits are filled in from long term memory by reference to the visuo-spatial short term memory trace during recall.

An unexpected aspect of the present study was the observation that day-month sequencing seemed to *increase* the beneficial effect of presenting digits in a keypad format on the proportion of digits correctly recalled dependent variable. We had predicted that bootstrapping would either be attenuated (if it had an executive component) or remain constant (if it did not) but the observation that it seemed to increase in size under executive load was not expected. This was only observed on one of the two measures used: future work might shed more light on whether it is a robust observation. If it turns out to be so, it suggests that bootstrapping may represent a useful basis for the development of interventions which may help support memory in situations where executive functions are compromised such as, for example, stress (Ohman, Nordin, Bergdahl, Birgander & Stigsdotter, 2007) or in diseases such as Alzheimer's disease (Perry & Hodges, 1999). It also suggests more generally that when fewer executive (shifting) resources are available for memory, multimodal encoding is favoured, and therefore that perhaps one facet of some kinds of expertise is fast, efficient, multimodal memory encoding. This would certainly fit with evidence of expertise effects in memory (e.g. Chase & Simon, 1973).

A body of recent research suggests that sequential processing mechanisms may be intrinsically linked to spatial representations – with early sequence items represented to the left of space and later sequence items to the right (van Dijck & Fias, 2011; van Dijck, Abrahamse, Marjerus & Fias, 2013; Guida & Lavielle-Guida, 2014; Guida, Leroux, Lavielle-Guida & Noël, 2016; summarised and described as a 'mental whiteboard hypothesis' by Abrahamse, van Dijck, Marjerus & Fias, 2014). This poses a couple of issues for the present research. One is that the assumption that the sequencing task is an entirely non-spatial task may be incorrect. However, the bootstrapping effect – which is known to be susceptible to spatial interference and is also abolished by spatial tapping (Allen et al, 2015) – persisted under the sequencing load. Hence any spatial representations that were recruited by sequential memory encoding did not conflict with the spatial representations utilised in bootstrapping. The second issue is that bootstrapping – a phenomenon that highlights the link between spatial location and verbal sequential memory – may be a manifestation of similar spatial processes that contribute to sequential memory under the mental whiteboard hypothesis, perhaps with the addition of extra dimensionality to the default left-right co-ordinates.

Previous results (Darling et al, 2012; Allen et al, 2015) suggest that bootstrapping recruits long term visuospatial knowledge alongside simultaneous multimodal (verbal—visuospatial) representations. The present data add to this the observation that shifting-related executive functions are not needed to create the bindings amongst these representations. An embedded processes approach (e.g. Cowan, 2005) would argue that the bindings are encoded within an activated long term memory, in which case the present results suggest that such bindings do not fall within the executive attentional control. Alternatively, if separate storage components

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within a multimodal working memory are assumed, maintenance of such links are the kind of processes ascribed to the episodic buffer (Baddeley et al, 2011), and the episodic buffer can in turn be dissociated from shifting – typically held to be a role of the central executive (Baddeley, et al, 2001). Meanwhile, if using the time-based resource sharing framework (a model that is strongly focused on task switching) to understand working memory, then additional switching resources is not required to establish the bindings within bootstrapping tasks (consistent with Langerock et al, 2014). One possibility worth visiting in future research with bootstrapping stimuli is that the time-based model would suggest that responses with longer gaps between utterances would allow for greater refreshing: it would certainly be interesting to evaluate how such a pattern interacted with display type, though note that bootstrapping effects are generally thought to occur during encoding, rather than retrieval (Allen et al, 2015).

Currently, neither the present data, or other data from bootstrapping tasks, allow selection between these frameworks of working memory; rather they add a set of constraints that require to be modelled by theories of working memory. Bootstrapping-based tasks could, however, be applied to directly test the episodic buffer hypothesis: given that the episodic buffer is assumed to have a limited capacity (Baddeley, 2000), then there should be a limit on the number of dimensions that can be combined simultaneously in bootstrapping like tasks, and there should also be a limit on the number of short term memory tasks that invoke long term memory binding (of which bootstrapping is one) that can be conducted simultaneously. These proposals go to the root of the episodic buffer and should be tested experimentally.

It is also useful to consider what other aspects of cognition the bootstrapping effect might illuminate, that is, to speculate about why it would be useful to have a system that has these characteristics of being automatic, multimodal and linked to long-term memory. Recently we have gently speculated that the functions seen in bootstrapping may be related to automatic binding processes that link constellations of information that are co-activated at a given moment in time (Darling et al, 2017). These information streams might be either directly driven by perception, or formed from the interaction of perceptual and working memory elements interpreted within the context of information stored in long term memory, creating a kind of constantly updated 'moving window' epoch of linked events over durations of a few seconds. This kind of transient schema could form a basis for subsequent episodic encoding. Put simply, it is possible that bootstrapping indexes a process which coagulates information for the purposes of writing to episodic long term memory. If so, bootstrapping, offers a mechanism to investigate and illuminate the processes invoked by that role. These are important questions for future research.

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Figure Captions

Figure 1. Display conditions, each showing how the sequence 3,1,4,2,5 would be presented. Each digit was visible for 1500ms, with an inter digit interval of 250ms, followed by a 1000ms retention interval prior to recall.

Figure 2. Graph showing total correct trials (TCT: /20) across display type and secondary task. Error bars show +/- 1 standard error.

Figure 3. Graph showing proportion of items per trial answered correctly (PDCR) across display type and secondary task. Error bars show +/- 1 standard error.

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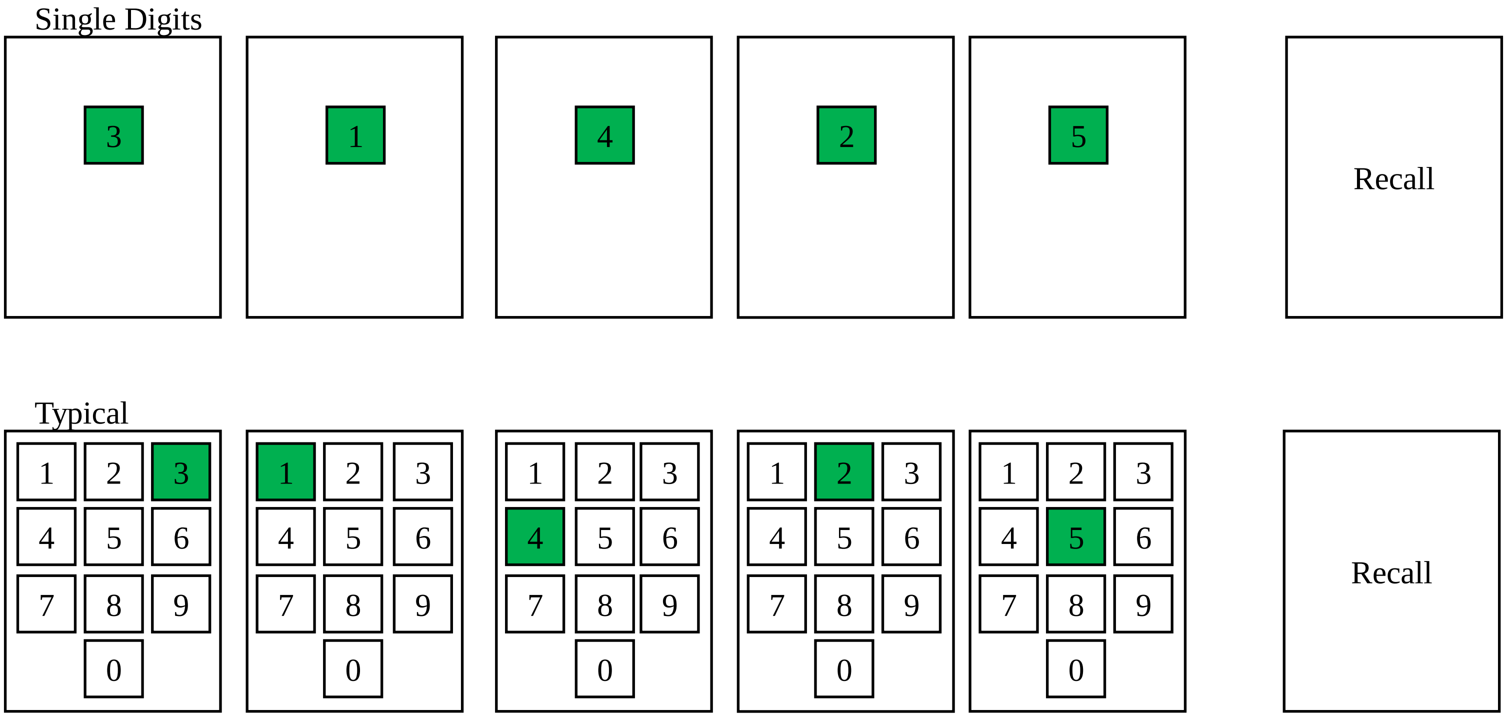
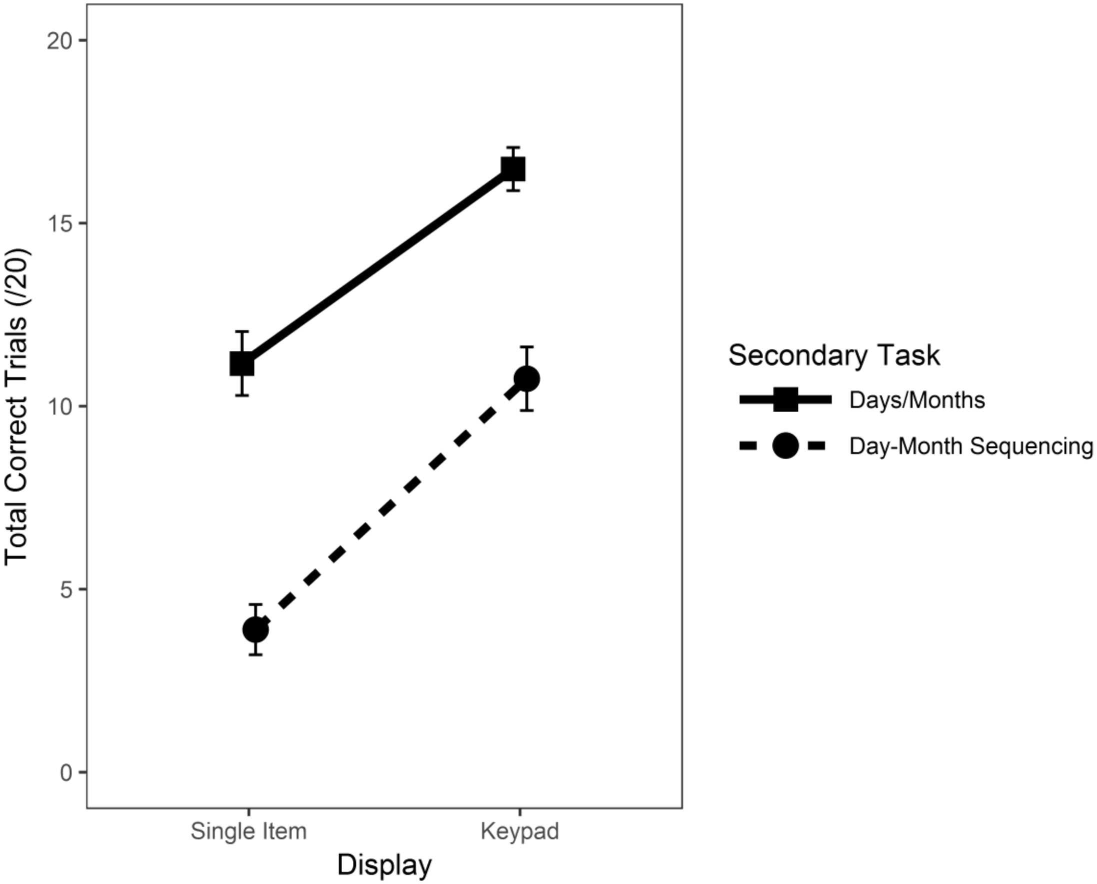

Single Digits
3
1
4
2
5
Recall
Typical
1 2 3 4 5 6 7 8 9 0
Recall



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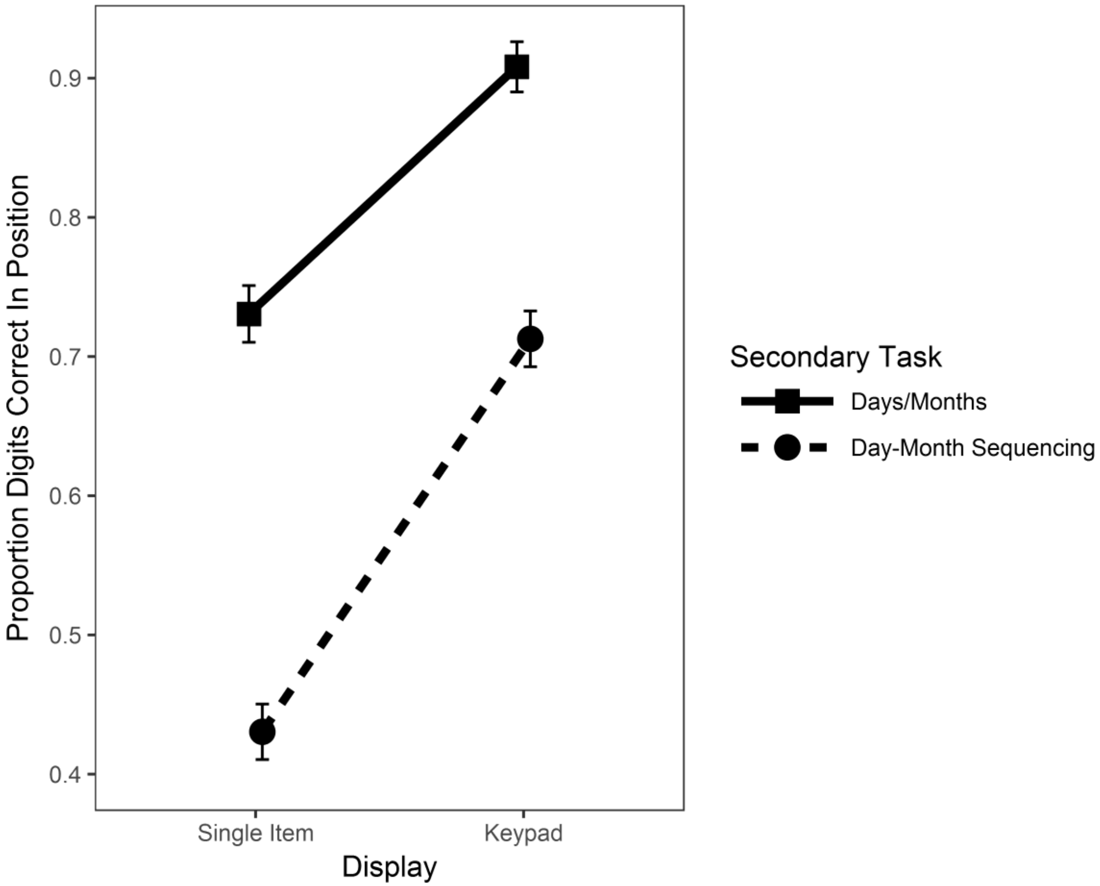

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