Synergies between processing and memory in children's reading span

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Abstract

Previous research has established the relevance of working memory for cognitive development. Yet the factors responsible for shaping performance in the complex span tasks used to assess working memory capacity are not fully understood. We report a study of reading span in 7- to 11-year old children that addresses several contemporary theoretical issues. We demonstrate that both the timing and the accuracy of recall are affected by the presence or absence of a semantic connection between the processing requirement and the memoranda. Evidence that there can be synergies between processing and memory argues against the view that complex span simply measures the competition between these activities. We also demonstrate a consistent relationship between the rate of completing processing operations (sentence reading) and recall accuracy. At the same time, the shape and strength of this function varies with the task configuration. Taken together, these results demonstrate the potential for reconstructive influences to shape working memory performance among children.

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Working memory has been described as "*the ability to simultaneously maintain and process goal-relevant information*" (Conway, Jarrold, Kane, Miyake, & Towse, 2007) and similarly, albeit in more metaphorical terms, as "the workbench of cognition" (Klatzky, 1980). Both descriptions draw attention to the notion of active memory processes that go beyond just maintenance of temporary information over short intervals. Accordingly, considerable effort has been invested in developing and testing tasks that combine the maintenance and processing of information. In this paper, we demonstrate that the relationship between processing and memory among children may be much more subtle and multi-faceted than commonly recognised, with implications for the construct of working memory capacity and its known links to wider achievement domains.

The original logic behind the family of complex span tasks known as working memory span (Daneman and Carpenter, 1980) was that they required simultaneous processing and memory operations, in contrast to simple span tasks such as word span that focus only on memory (although see Colom, Rebollo, Abad & Shih, 2006 for a recent interpretation of this distinction). For example in *reading span*, a participant processes a sequence of sentences for comprehension and then attempts to remember a word allied to each sentence, and in *counting span*, a participant determines the numerosities of a sequence of visual arrays and then attempts to remember all the count totals (Case, Kurland & Goldberg, 1982). Working memory span reflects the upper limit on the number of target items, words or count totals in these examples, that can be recalled in sequence (see Conway et al., 2005, and Friedman & Miyake, 2005, for discussion of different indices of memory performance).

Early theoretical accounts of what determines working memory span emphasised the notion of limited cognitive resources shared between processing and memory demands (Daneman & Carpenter, 1980; Case et al., 1982). According to this resource-sharing framework, processing (e.g. reading comprehension or counting) and memory (retention of some accompanying memoranda) requirements are serviced by a common limited capacity system, which results in a trade-off in resources. Thus span reflects the balance between processing and memory processes. This theoretical perspective emphasises the assumption that there is a strong, direct, and competitive relationship between processing and retention in working memory (Daneman & Hannon, 2001).

Subsequent accounts have challenged the ubiquity and generality of the resource-sharing view among children. Towse & Hitch (1995) manipulated a counting span task in terms of both processing difficulty (the amount of resources required to support processing) and processing duration (the exposure of the memoranda to forgetting processes). Children obtained lower span scores when the processing was harder, but this effect disappeared when controlling for the duration of processing (see also Ransdell & Hecht, 2003; Barrouillet & Camos, 2001, Expt. 1 & 2). These results suggested that processing time was more important than processing intensity in shaping absolute levels of complex span. The findings motivated a 'task-switching' hypothesis, according to which processing and memory are sequential rather than simultaneous activities and memory representations become less accessible during time devoted to processing operations (Towse, Hitch & Hutton, 1998; and for attempts to compare and integrate resource-sharing and time-dependent approaches, see Barrouillet, Bernadin, & Camos, 2004; Jarrold & Bayliss, 2007; Towse, Hitch & Horton, 2007).

The current study does not focus solely on the contrast between these accounts, but instead draws on conceptual threads relevant to both and argues for more richly elaborated models of working memory. In particular we identify three separate yet connected research issues addressed in the current empirical work. These three issues focus on the specification of the functional relationship between processing duration and recall accuracy, the reconstruction of recallable items, and the relevance of stimulus similarity for recall performance. We address each of these in turn.

<u>The relationship between processing duration and recall accuracy</u>

The major theoretical positions outlined above also make predictions for individual differences in recall ability as a function of the time occupied by processing operations. For example, if sequence accessibility is compromised by protracted processing requirements, then participants with relatively a slow processing speed - who thereby are faced with a longer retention time for a given set of materials - should remember less. Indeed, Towse et al. (1998) found that less efficient processing was associated with lower counting spans, operation spans and reading spans among 8- to 11-year-old children. Likewise, Jarrold and Bayliss (2007) discuss the outcome of multiple studies in which processing tasks were completed on their own as well as when combined with memory requirements in complex span. They conclude that processing time is one (albeit not the only) predictor of recall performance.

Does the same relationship between speed and span hold across different working memory tasks or domains? In other words, is the rate of forgetting equivalent irrespective of the nature of processing? This issue speaks to whether there a single functional relationship linking the task elements among children. The task-switching model outlined above suggests only that information loss occurs when one is ‘switched out’ of memory activities; the precise rate of this loss may be dependent on a range of potential factors such as the potency of intra-list interference (Hitch, Towse, & Hutton, 2001) or the endurance of memory representations (Towse, Hitch, Hamilton, Peacock & Hutton, 2005). In contrast, resource-sharing views in which processing time is a proxy for the amount of resources consumed by processing (see e.g. Case et al., 1982) come closer to positing a single function.

A single function is explicit in the time-based resource-sharing model (Barrouillet et al., 2004) according to which span is a function of the cognitive load of a task, indexed by the duration of attentional capture while performing processing operations divided by the total trial time (see also Barrouillet & Camos, 2007). However it is important to note that evidence for this model arises particularly from paradigms that involve discontinuous processing tasks such as paced digit naming that leave unfilled intervals, unlike the more continuous processing and retention cycle typical of complex span paradigms. The model assumes that slower processing both increases forgetting due to decay during processing operations and decreases the opportunity to refresh memory traces during unfilled intervals. It thus emphasizes micro task-switching phenomena *within* processing and retention episodes as well as macro task switching *between* these dimensions (Towse & Hitch, 2007).

Whilst there are some correspondences between this and the task-switching model, the time-based resource sharing model differs because it (a) accounts for recall purely terms of temporal parameters during encoding and (b) specifies a detailed role for unfilled time in intermittent processing tasks. In contrast the task-switching model acknowledges that forgetting may be due to factors such as interference besides or instead of decay and was not specified to consider unfilled intervals into complex span tasks (although see Towse, Hitch & Hutton, 2002, for some elaborations).

Hitch et al. (2001) reported data from operation span (simple arithmetic sums were solved and the answers retained) and reading span (unfinished sentences were read and the completion word retained) administered to 8 – 11-year-old children. In both cases, the time to complete the processing component of the task was negatively correlated with span. However, the slope of the best-fitting line was steeper for operation span than for reading span. A single slope account of performance did not fit the data. Hitch et al. (2001) interpreted these results in terms of task-switching, suggesting rates of forgetting that differed for each type of processing activity.

However, reading and operation span also differ in the nature of the memoranda (words and numbers) and the mean length of sequence recalled (since operation span scores were generally higher). Thus the findings need not be incompatible with a cognitive load explanation since different processing activities are called upon and thus the extent of attentional capture may be different. In the present research, we consider the speed–span relationship for two working memory tasks that involve the same processing component (sentence completion) and equivalent memory stimuli (words unique to each trial). We argue that this makes for a much more compelling examination of the single slope assumption.

The reconstruction of recallable items

Cowan et al. (2003) also considered the temporal dynamics of complex span, yet the focus was on the timing of recall. The pauses between words in children’s and adults' reading span were found to be much longer than is commonly found in simple span memory tasks. Long interword pauses during recall were also characteristic of listening span (verification of heard sentences) but less so for counting span. Cowan et al. argued that the greater length of reading / listening span pauses indicated that participants could use information from linguistic processes to scaffold recall of the target words during output. The shorter interword pauses in counting span were attributed to the low distinctiveness of the processing operations associated with each target item in this paradigm, rendering ineffective a reliance on memory from processing.

Towse, Cowan, Hitch & Horton (2008) provided more direct evidence that adults’ reading span incorporated reconstructive processes during recall. Over a series of experiments, they compared two reading span configurations; one in which the memoranda were sentence words and thus *integrated* with processing content, and another in which memoranda were words unrelated to the sentences and thus *independent* of processing content. In the former condition, participants can potentially use memories of the sentence content to facilitate recall of target words. However, this is not plausible in the latter case since there is nothing inherent in any memory of the sentence to cue the target word.

Towse et al. (2008) consistently found that recall accuracy was higher and interword pauses were longer in the integrated condition than independent condition. This supported the recall reconstruction hypothesis, the notion that when the opportunity exists, memory for processing operations can be used to revive or corroborate memory for target items. Importantly, this challenges the common assumption identified earlier that any relationship between processing and memory in working memory tasks is necessarily *competitive*. Towse et al. argue instead that, depending on the nature of the task, there may be a *cooperative* relationship between processing and memory in complex span. In the present research, we therefore analyse the chronometry of recall for integrated and independent reading span formats among children; this allows us to identify whether patterns of adult performance are replicated in children, or alternatively whether reconstructive processes are the result of a mature strategy seen only in adults.

In this context, it is worth noting that Unsworth and Engle (2007) have proposed that adult individual differences in complex span are related to the distinction between primary and secondary memory processes. They argue that central to complex span performance is the need to regulate search strategies efficiently in secondary memory (see also Healey & Miyake, 2009). The recall reconstruction hypothesis shares several features with this approach, in particular focusing on cued recall utilizing multiple source representations. A comparison between these theoretical accounts also emphasises that even though the present research design focuses on *semantic* support for memory from sentences, reconstruction of output is a more general process that can involve search on a range of different coding dimensions

<u>Stimulus similarity in working memory span</u>

Conlin, Gathercole & Adams (2005) draw attention to yet another aspect of the relationship between processing and recall. They argued that working memory span can be affected by the similarity or overlap between the content of processing and memoranda (for a wider perspective from adult data, see Oberauer, Lange & Engle, 2004). They asked children to carry out a reading span or operation span task (i.e. involving linguistic and numerical processing domains respectively) with either words or numbers as memory stimuli. They found superior levels of recall when the content of processing and the memoranda were categorically distinct (i.e., reading span coupled with recall of numbers or operation span coupled with recall of words) and argued that processing operations have greater interfering power when they overlap with the representations of items held in memory (see also Saito & Miyake, 2004).

The memorial advantage for items from a distinct stimulus class occurred even though reading span involved memory for sentence completion words (Expt. 1). Conlin et al. pointed out that sentence memory ought to have helped recall of within-category items here, and this was taken as a lack of evidence for reconstructive processes. However, while the case for the potential relevance of within-domain interference is well made, we view these results as equivocal with respect to the contribution of recall reconstruction processes in reading span. This is because Conlin et al.'s design confounds the manipulation of stimulus similarity (whether the memoranda share the same stimulus class as processing events) with the presence or absence of semantic links between processing and memory.

In the current study, since we compare integrated and independent task formats for reading span alone, we isolate the opportunity for reconstructive processes using a consistent stimulus class for memoranda. Indeed, if stimulus similarity alone is paramount in determining recall performance, there is an argument that children will recall fewer items from the integrated condition, since there is more overlap (i.e. opportunity for confusion) between processing content and memoranda than for the independent condition.

Summary

It is possible to understand many current views of working memory capacity in terms of a competitive relationship between processing and storage elements of complex span. This holds whether one suggests processing consumes resources that would otherwise be available for retention, or occupies time during which memory traces degrade due to decay or interference through the prevention of active maintenance. A general limitation in such approaches is that they have not been elaborated to identify exactly which aspects of processing are relevant to the fate of memoranda.

They are all broadly consistent with evidence for negative correlations between processing duration and recall accuracy in complex span tasks. However, among many questions left open is whether there is a common function relating processing time and recall across different tasks. The formal specification of recall within the time-based resource-sharing model points to a single quantitative relationship between processing time and memory performance - but Hitch et al., 2001 provide a potential exception to this. Recent adult research offers an additional perspective too, in showing that reading span can involve substantial reconstructive processes, leading to a cooperative relationship between processing and retention.

The current study paves the way for a careful consideration of these issues by examining the relationship between processing time and reading span as a function of whether the target memory items are related to the processing operations or unrelated. Studying children and measuring the temporal dynamics of the recall process allows us to generalise previous findings obtained with adults and assess whether they reflect use of mature strategies. Moreover, manipulating the overlap between the content of processing and the target item will provide more detailed data on the role of stimulus similarity in complex span (Conlin et al., 2005). The ages sampled here encompass a much-studied cohort with respect to the development of complex memory span and thus speak to an existing research literature. Moreover, reading skills should be sufficiently advanced to enable reading span tasks to be widely administered without the processing requirements being prohibitively demanding for many children.

Methodologically, previous research has shown that children often do not progress beyond correct recall of more than 3 item sequences in reading span (e.g. Towse, Cowan, Horton, & Whytock, 2008). Therefore, to facilitate task administration, we presented children with two-item and three-item memory sequences, rather than attempting to identify span length for each child. This permits greater focus on performance-critical sequences.

Method

Participants. The study involved 108 participants organised into three age groups by school class (36 children per group); the youngest group had a mean age of 7 years 7 months (ranging between 7;0 and 8;1), the intermediate group had a mean age of 9 years 0 months (ranging between 8;4 and 9;9) and the older group had a mean age of 10 years 8 months (ranging between 10;0 and 11;2). Children were assigned at random to the integrated and independent word condition with half the children in each condition.

Stimuli. The sentence stimulus pool comprised a corpus of 88 sentences (based on medium-length stimuli described in Towse, Hamilton, Hitch & Hutton, 2000). The stimulus pool was divided into two equal subsets, one of which (allocated at random) was used to generate the 25 test sentences for each child. Sentences typically contained 8-10 words and had been formulated to elicit target completion words reliably (e.g., "While I was sleeping I had a strange" usually leads to the completion response "dream"). Independent words were yoked to each sentence and checked to minimise any obvious semantic relationship. They were drawn from the alternate set of sentence items, ensuring that across children, independent and integrated memoranda were the same.

Apparatus. Computer events were driven by an Apple Macintosh ibook G4 (programmed using the “Revolution” language running under OS X) with response latencies measured in (1/60 s) ticks. Audio recordings were captured directly to minidisk (Sony MZ-N710, with a Sony ECM-DS70P microphone).

Procedure

Children were assigned to either the integrated or the independent condition. Once they had been introduced verbally to the task requirements by the experimenter, they were given a practice sentence to read (as the sole task). On each experimental trial, a sequence of two or three incomplete sentences appeared sequentially on screen. Participants read each sentence aloud and generated an appropriate completion word. In the integrated condition, this final word formed the memorandum, and after they had announced their choice this word appeared and there was a 1 sec interval before the next sentence or the recall cue appeared[1]. In the independent condition, once children completed the sentence, the memorandum appeared (in purple) for .75 s surrounded by a 1.25 s ISI during which time children were asked to read the memorandum, before the next sentence or the recall cue appeared.

Following the visual recall cue (accompanied by an auditory tone), children attempted serial recall of the memoranda. Trials commenced with 5 sets of 2-sentence sequences, followed by 5 sets of 3-sentence sequences. Participants knew the list length prior to each trial.

Results

Developmental changes in reading span and the effect of integrated vs. independent processing

A number of different measures of recall accuracy have been constructed reflecting both maximum sequence length and words recalled in serial order (Conway et al., 2005; Friedman & Miyake, 2005). Given that we administered only two sequence lengths, we report recall accuracy in Table 1 as the total number of words recalled in the correct serial position, with a theoretical range between 0 and 25. Analysis on memory performance with age and semantic connection as factors, confirmed substantially higher levels of recall in the

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[1] Only very rarely did children produce an alternative completion; the experimenter would read out the memorandum preceded by "Or..." to underscore the visually shown word as the memory target.

integrated word condition, $F(1,102)=29.7$, $p<.001$, $\eta_p^2=.226$, and among older children, $F(2,102)=11.8$, $p<.001$, $\eta_p^2=.188$. The interaction between these factors was not significant, $F(2,102)=1.36$, $p=.261$, $\eta_p^2=.026$.

The relationship between processing speed and recall ability

The data analysed by Hitch et al. (2001) considered the functional relationship between processing time and memory recall with respect to cross-sectional and longitudinal differences in children's ages. Using group means, they found two 'developmental growth curves' with operation span changing more rapidly as a function of processing time than reading span. We have replotted those original data at the level of individual children (data points averaged across multiple tasks) expressed as z-scores so that they can be compared more easily across materials and sample. The data are shown in Figure 1.

The function for operation span (y) involved a regression line with

$y = -.593(x) + .294$

where x is the time to complete an arithmetic sum. The corresponding function for reading span (y) is also reported, and the regression line in this case was

$y = -.267(x) - .444$

where x is the time to comprehend and complete a sentence. The figure and regression equations indicate that the slope is more shallow (less than half the gradient) in the case of the reading span task, but does not address whether this might be a range effect.

Corresponding analysis on the current dataset was also based on processing times and recall accuracy (the number of words recalled correctly and in serial order). The time to complete sentence reading was screened for outliers, by examining the z-score distribution for the corpus of sentences at each serial position. Reading times of $z>3.29$ were trimmed back (Winsorized) to the threshold interval. Sentence durations were then averaged across serial position and trial for each child. Finally, this dataset was converted to z-scores.

In the *independent* condition, where memoranda are unrelated to the sentences processed, the relationship between processing and memory is best described by the regression equation

$y = -.412(x) - .412$

Data from the *integrated* condition, in which memoranda came from the end-of sentence words were best fit by the following linear regression function

$y = -.730(x) + .409$

Scatterplots for both conditions are shown in Figure 2 along with the best-fitting regression line. In both cases there is a negative slope showing that children with longer processing times recalled less information. This provides general confirmation of previous results. We address two issues in the specific functions mapping recall to processing time.

First is the comparison between integrated and independent conditions. As captured by the regression equations, the slope gradient was steeper (almost twice as large) in the integrated condition. A Chow test compared the equality of regression parameters, with respect to both the intercept and the slope values. This confirmed differences between the conditions, $F(2,103)=21.9$, $p<.001$, $\Delta R^2=.204$. Specific comparisons indicated differences in the slopes, $t(103)=2.50$, $p=.014$, $\eta^2=.057$, with a greater rate of change in the integrated condition. There was also a difference in the intercepts, $t(103)=4.45$, $p<.001$, $\eta^2=.184$, reflecting superior recall in the integrated condition.

Second, we consider the current dataset in relation to Hitch et al. (2001). Whilst both are described as z-scores to make comparisons easier, the gradients in the current dataset are steeper, as shown in Table 2, which also describes the correlation between recall and processing time.

There is consistency across datasets in terms of the *strength of association* between recall accuracy and processing time. Where the task affords the opportunity for processing content usefully to scaffold recall, the association is stronger. Thus, the correlation -and R^2 fit values in Figures 1 and 2- are higher for integrated compared with independent formats in the current data, and reading span compared with operation span formats for Hitch et al. (2001). Thus, processing duration is a more accurate predictor of recall when the activity is relevant to recall and plausibly supports it.

There is a different pattern of alignment with respect to the *slope parameter* or rate of forgetting. Hitch et al.'s reading span task involved an integrated word format and so one might anticipate similar performance to the current integrated condition. Yet the slope for the integrated word condition was steep, significantly more so than in the independent word condition. We therefore suggest that when the memoranda are linked to the sentences that have been read, the impact of processing time differences is especially systematic and dramatic. In contrast, in the independent word condition (where children cannot easily draw on the sentences as a reconstructive aid), alternative memory strategies may be at play. Whilst these are affected by reading time - since the correlation is non-zero - its impact is less dramatic.

The chronometry of recall

Recall times were extracted from correctly recalled trial sequences (leading to less data from 3-word than 2-word sequences). This ensured that item production and pause latencies reflected successful processes, and avoided biases from erroneous recalls that are differentially distributed in frequency across the study data. Additionally, some data were excluded because recall timing was 'contaminated' (e.g., when a participant restarted their list or asked for clarification about recall, or when the participant initiated recall before the recall signal, thereby rendering the preparatory interval inappropriate).

Spoken recall was segmented into three contiguous phases (see, for example, Cowan et al., 1998); (a) the preparatory interval; the time between the recall signal and the start of recall, (b) word durations; the time to articulate the relevant words and (c) interword pauses; the gaps between recall words. A single trained researcher extracted timing values[2]. Specific recall time segments were screened for outliers by examining z-score distributions of each time measurement; an outlier was labelled as such when $\underline{z}>3.29$, and outliers were trimmed back to the relevant time limit. Table 3 reports the sample sizes available for analysis and Figure 3 shows the duration of each recall component, collapsed across age because of small sample sizes in some experimental cells.

Focusing on the interword pause in two-word sequences, there were significantly longer pauses in the integrated compared with the independent condition, $F(1,70)=7.26$, $p=.009$, $\eta_p^2=.094$. There was also a marginal age effect with older children producing quicker responses, $F(2,70)=2.96$, $p=.059$, $\eta_p^2=.078$, but no reliable interaction, $F(2,70)=1.73$, $p=.184$, $\eta_p^2=.047$. There were fewer correct three-word sequences for analysis. Nonetheless, the first interword pause was significantly longer in the integrated compared with the independent

[2] A sample of blind timings were compared using an independent coder working with a separate dataset. Measurements were highly correlated (for a sample of 101 interval measurements, $\underline{r}(99)=.999$) and matched in absolute terms (mean gap lengths differed by less than 10 ms).

condition, $F(1,24)=5.99$, $p=.022$, $\eta_p^2=.200$ [with no significant age effect, $F<1$, $p=.857$, $\eta_p^2=.013$, or interaction, $F<1$, $p=.851$, $\eta_p^2=.013$]. The second interword pause was also significantly longer in the integrated condition, $F(1,25)=6.55$, $p=.017$, $\eta_p^2=.208$ [again with no age effect, $F<1$, $p=.838$, $\eta_p^2=.014$, or interaction, $F<1$, $p=.702$, $\eta_p^2=.028$].

Finally, we examined individual differences in output timing and recall. Consistent with other studies investigating the chronometry of recall, response accuracy was negatively correlated with the length of the interword pause in two-word and three-word sequences, $r(73)=-.261$, $p=.037$ and $r(28)=-.133$, $p=.483$ respectively.[3] Neither the interword pauses, nor the overall recall duration, correlated with the time to complete the sentence processing requirements (all *rs*<.182). In other words, the chronometry of recall is not just a global speed-of-processing variable, but instead reflects process-specific events.

In summary, the data reveal that accompanying higher levels of recall in the integrated condition, there were longer pauses between the correct production of

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[3] Since these outcomes may have been modulated by the principal experimental variable (which as already reported affects both accuracy and pauses) we repeated these analyses separately for each condition. With independent words, the recall pause - accuracy relationship was negative and non-significant for both two- and three-word sequences, With integrated words, the two-word correlation was negative, and the three-word correlation positive, yet neither was significant.

words, at each of the sequence lengths analysed. At the level of individual differences, there was a tendency for faster retrieval to be associated with better recall, but this was a small effect and reliable only for the shorter (initial) trials.

Discussion

We introduced and motivated the present study by focusing on three question domains in the research literature. To structure the discussion, we therefore turn to each of these areas specifically, and then conclude by offering more integrative comments.

The relationship between processing duration and recall accuracy

The data reconfirm the systematic and consistent relationship that exists between processing time and memory performance in children's working memory, which is consistent with other datasets (e.g. Hitch et al., 2001; Bayliss et al., 2003). At the same time, it contrasts with data from adults, where experiments have concluded that processing time does not correlate with recall accuracy (e.g. Towse et al, 2000). Importantly, the present data show more subtle phenomena than simply a contrast between the presence / absence of a speed / span relationship. Results demonstrate this relationship is not the same for all versions of reading span task as there are differences between the integrated word format and the independent word format, both with respect to the strength of the relationship and the form of the relationship (the gradient of change in recall as a function of processing length).

These results have implications for a number of theoretical accounts of working memory. In particular, it provides an exception to the ‘single slope’ assumption relating span to processing time (Barrouillet et al., 2004; Case et al., 1982) and suggests that this assumption may need to be reconsidered or its generality curtailed. More generally, the data provide a challenge to the notion of processing time as a proxy for a global measure such as resource utilisation. Such a stance may certainly retain important heuristic value. Yet when examined in detail, this leaves important questions unaddressed. In essence, such global approaches to understanding the temporal context of children’s working memory tasks are not sufficiently rich to satisfactorily account for working memory performance. We consider two aspects to this argument.

First, the current findings demonstrate that processing activity not necessarily in conflict with the retention of experimentally defined target memoranda. Instead, we argue that there may be cooperative or symbiotic forces that can link memory with processing content. Consequently it is important to appreciate *what* processing takes place in addition to just *how long for*.

Second, the present data converge with other recent work (e.g., Cowan et al. 2003; Towse, Cowan et al., 2008) in demonstrating a distinction to be made between effects of time in the maintenance phase as well as the recall phase. In the former case, when memory activities occur alongside ongoing cognition, faster processing is beneficial since participants arrive at the point of recall with a more functional / better preserved ensemble of representations. Yet in the latter case, with respect to the comparison of integrated and independent formats *at output*, slower processing accompanies better recall. Such findings are not necessarily in conflict with each other. During sentence presentation and comprehension, processing can be thought of, loosely, as restricting the opportunity for memory activities. At recall also, a swift sequence production is in general a chronometric signature of highly accessible memories. With respect to sequence production in the integrated condition, however, where the processing content has relevance for the to-be-recalled items, slower processing can reflect a beneficial, that is facilitative cognitive process. Here, the delays in response production are consistent with participants utilising contextual information to increase the accuracy of recall.

We therefore suggest that holistic approaches to conceptualising processing times are likely to struggle in explaining the true complexities of the empirical data (noting also evidence that performance is not static, but changes as a function of task experience; Towse, Cowan, Horton et al., 2008). The trajectory of memory representations over time (ie. the fidelity of memory representations) differs according to the semantic richness of those representations. This variable also affects the strength of the processing speed-recall accuracy correlations. When the representations are isolated words and are not anchored in any natural way to the sentence reading that occurs alongside, then the contribution of processing time to individual differences in recall is both relatively small and relatively "gentle". When the representations are semantically bound to the accompanying processing (when sentence comprehension is relevant to items designated as memoranda), the contribution of processing time to individual differences in recall is both larger and is more harmful to recall.

The data do not permit a definitive explanation about cognitive processes here. We suggest, however, that with integrated words children have multiple representations, not just of the memoranda but also from the sentences too. Perhaps with integrated words, efficient readers generally develop stronger representations that support effective memory, leading to a tight relationship between variables in this condition. As a consequence there is more information to lose and recall performance is especially hurt by retention delays. In the independent condition, representations may be more sparse, and therefore other strategies may be used to keep memoranda active, such as item / sequence rehearsal. As a result, the contribution of processing length may be less critical than other, strategy-specific factors that shape recall success. Above and beyond these details, the subtlety of the data reinforce the need to weave different explanatory strands together to understand the temporal dynamics of working memory span.

The reconstruction of recallable items

Towse, Cowan, Hitch et al. (2008) found that, among adults, reading span benefits from the presence of a semantic connection between the content of processing and the memoranda. There are longer pauses in sequence recall, which offers converging evidence that memoranda are produced with the aid of additional time-consuming recall processes. The present data demonstrate a developmental continuity since a semantic link between processing and retention facilitates recall among children of different ages and the effect is statistically equivalent for 7- as well as 11-year-olds. Moreover, we obtained a statistically large effect with respect to the interword pause difference between integrated and independent word formats. Thus the present findings are taken to suggest that in the integrated condition children reconstruct recall items rather than utilise a complete and fully-assembled memory sequence.

In the present experiment, participants remembered either the words they generated to complete the sentences or separate, unrelated items. This raises the question; is item generation or the presence of a semantic connection the relevant factor that produces the recall time/accuracy profile? Towse, Cowan, Hitch et al. (2008) found an effect of semantic relatedness among adults irrespective of whether or not participants remembered self-generated items (though generation may have contributed to the magnitude of phenomena). Thus, it appears implausible to attribute the current effect to self-generation alone. Moreover, explanations of the generation effect actually overlap with recall reconstruction, in that generation processes may enhance and enrich the representation of the memoranda.

It is not claimed that reconstruction occurs for every item in the recall sequence, just that it is detectable in the aggregate of performance. Nor have we considered performance of still younger children, who are less likely to spontaneously engage in strategic behavior in immediate serial recall (Flavell, Beach, & Chinsky, 1966). Nonetheless, the current study demonstrates that when the opportunity arises children consider a much richer set of representations than just experimentally defined memoranda.

It is also important to note that the representations supporting recall may well go beyond episodic information about earlier processing; this contextual dimension has simply been the vehicle by which we have explored the general principle. We suggest that there can be multiple sources of reconstructive information in working memory and information from processing may just be one that is highly salient to individuals when the task has an integrated format. Thus, the principle of reconstruction emerges from the more general proposition that in working memory tasks, memoranda may not be actively and continuously maintained throughout the retention interval (Cowan et al., 2003; Haarmann, Davelaar & Usher, 2003; Towse et al., 1998; Towse, Hitch, Hamilton & Pirrie, 2008; Unsworth & Engle, 2007). Semantic reconstruction can be regarded as one example of cue-mediated recall from secondary memory traces (see also Healey & Miyake, 2009; Unsworth & Engle, 2006).

Stimulus similarity in working memory span

Several recent datasets with children and adults indicate that stimulus similarity or the overlap between processing content and memoranda is relevant to working memory (e.g., Conlin et al., 2005; Oberauer et al., 2004; Saito & Miyake, 2004). In the present study we compared an extreme or "super-sized" form of stimulus similarity – where the memoranda are integral to the sentence processing and not just from the same class of items – with a less extreme form of similarity – where memoranda are conceptually distinct, whilst still from the same class.

Superior levels of recall in the integrated condition suggest that the potentially beneficial contribution of sentences for supporting recall more than overcomes any detrimental impact from high stimulus similarity. Accordingly, stimulus similarity does not represent the whole story so far as recall performance is concerned. Reconstructive processes – where processing can facilitate identification of the target memory item – are the more influential task dimension here, just as the reverse may be true when memoranda categories are manipulated also (Conlin et al., 2005).

Indeed, rather than viewing stimulus similarity or representation-based interference and recall reconstruction processes as competitive dimensions, we argue that these accounts are better thought of as potentially complementary to each other. Essentially they each emphasize how, in complex span, processing and memory activities are not independent of each other. Whilst they differ in emphasizing the deleterious or supportive roles of processing, it is apparent that their predictions are context-dependent, in that the impact of processing activity will depend on the details of its relationship to memory requirements. Moreover, the data echo the views of Oberauer et al. (2004) in suggesting that accounts of interference between processing and memory need to be specific in terms of exactly what type of interference is potentially involved.

Conclusion

In most studies, working memory tasks are used to derive a single performance index: the amount recalled. This measure is coherent and internally reliable, and reliably predictive of many higher cognitive skills. Moreover it is clear that many different forms of working memory task, whether reading span or operation span (e.g. Hitch et al., 2001), working memory period (Towse et al., 2005) or combination tasks (Bayliss et al., 2003) all consistently predict these external measures. There is some core commonality to these different procedures, which the present findings argue is not simply *competition* between processing and memory phases of the task. It may instead reflect some higher-level attribute such as the management or combination of different and unfamiliar task requirements (Jarrold & Bayliss, 2007; see also Towse et al., 2008, for evidence that task novelty is important) and goal maintenance (Kane & Engle, 2003).

In the present study, we demonstrate that children's accuracy is affected by the dynamics of processing. Replicating previous work, we show that children who read more quickly are on average more likely to recall the target sequence more accurately. Reading time, we hasten to add, may be a proxy for some other causal process; but a key finding is that both the rate of forgetting and the strength of the processing speed - recall accuracy relationship depend on how the complex span task is constructed. Importantly, the present data also demonstrate that neither speed of processing during the maintenance phase, nor accuracy levels, fully capture the subtleties of working memory. We show that recall timing data can provide an important additional complementary source of evidence. This focus on recall allows us to confirm that children are sensitive to the opportunity to boost working memory by drawing on sentence processing where relevant, and that they do so precisely at the point of sequence recall.

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Table 1. Memory performance (number of correctly recalled words in their appropriate serial position). Standard deviation in parentheses.

	younger group	intermediate group	older group
Integrated condition	13.2 (4.97)	15.2 (3.79)	19.1 (3.04)
Independent condition	10.3 (4.16)	11.3 (2.50)	13.3 (4.40)

Table 2. The relationship between processing time and recall accuracy in the current study and for data reported by Hitch et al. (2001). Significance level associated with strength of association shown in parentheses.

	Strength of association	Slope parameter
Integrated:	-.734 ($p<.001$)	.73
Independent:	-.480 ($p=.001$)	.41
Rspan (Hitch et al.):	-.530 ($p=.001$)	.27
Ospan (Hitch et al.):	-.270 ($p=.017$)	.59

Table 3. Number of children with analyzable data available for chronometric assessment of reading span recall.

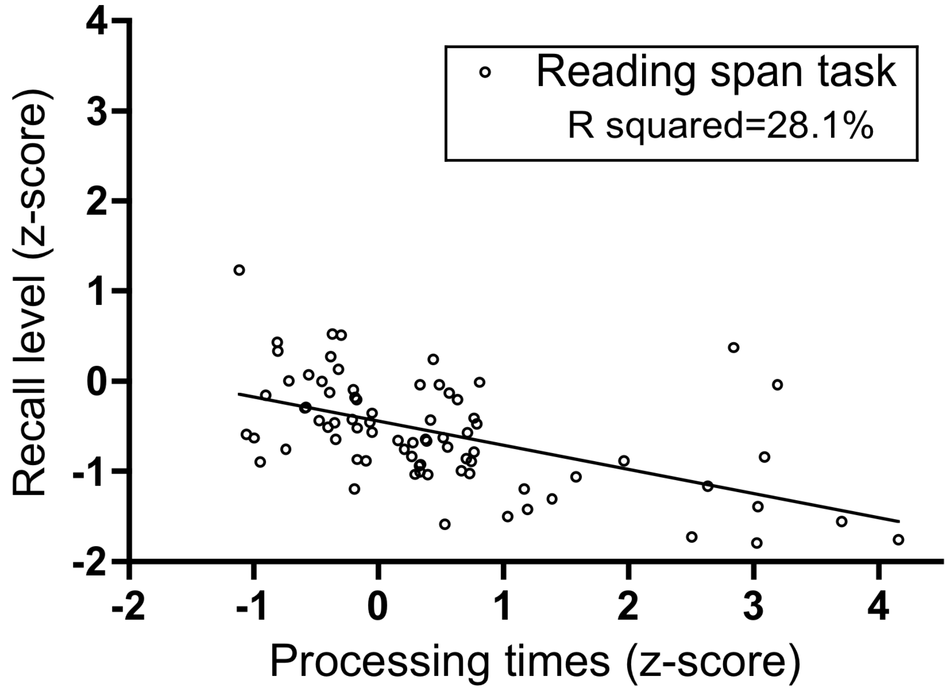
Age group:	younger	intermediate	older	Total
2-word integrated recall:	12	14	18	44
2-word independent recall:	10	10	12	32
3-word integrated recall:	3	8	11	22
3-word independent recall:	3	1	5	9

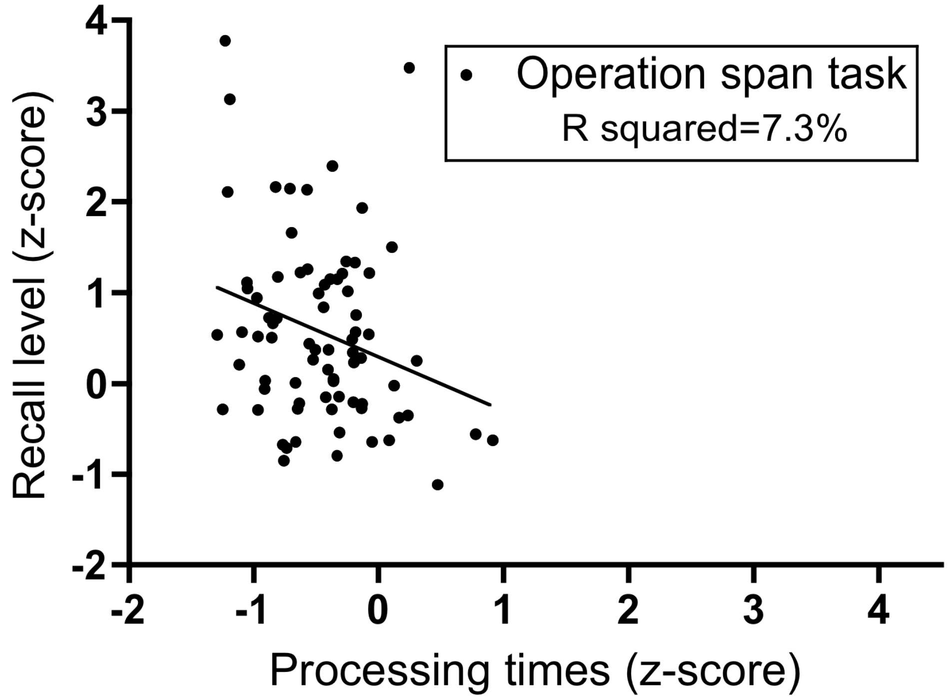
Figure captions

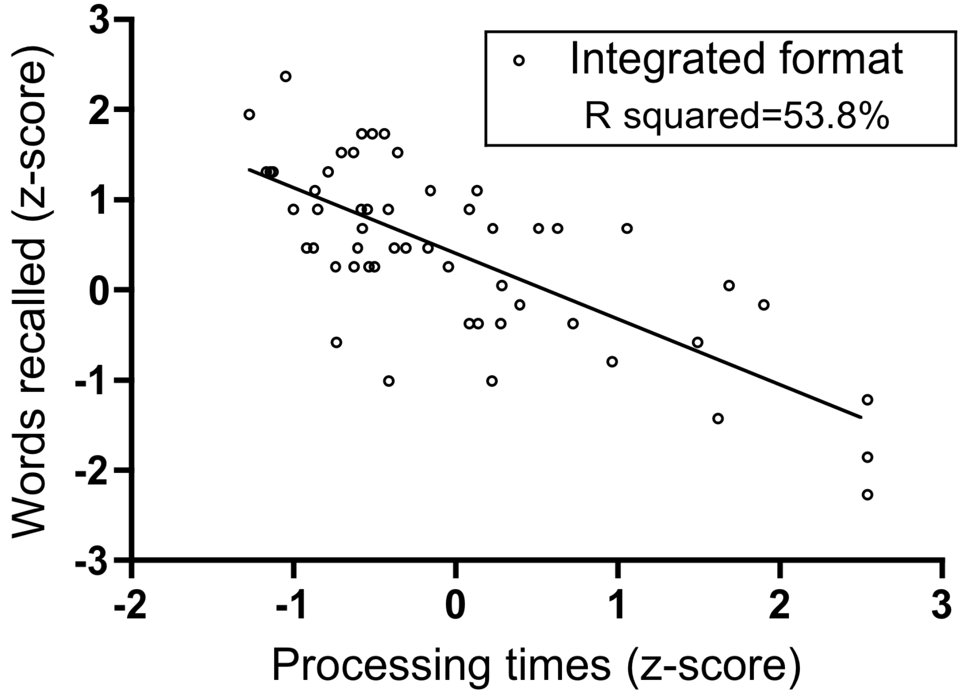
Figure 1. The relationship between time to complete processing requirements and memory recall reported by Hitch et al. (2001). Each variable is described as a z-score dimension. Upper panel describes the relationship for the reading span task, the lower panel describes the operation span task. The fitted line represents the linear regression function.

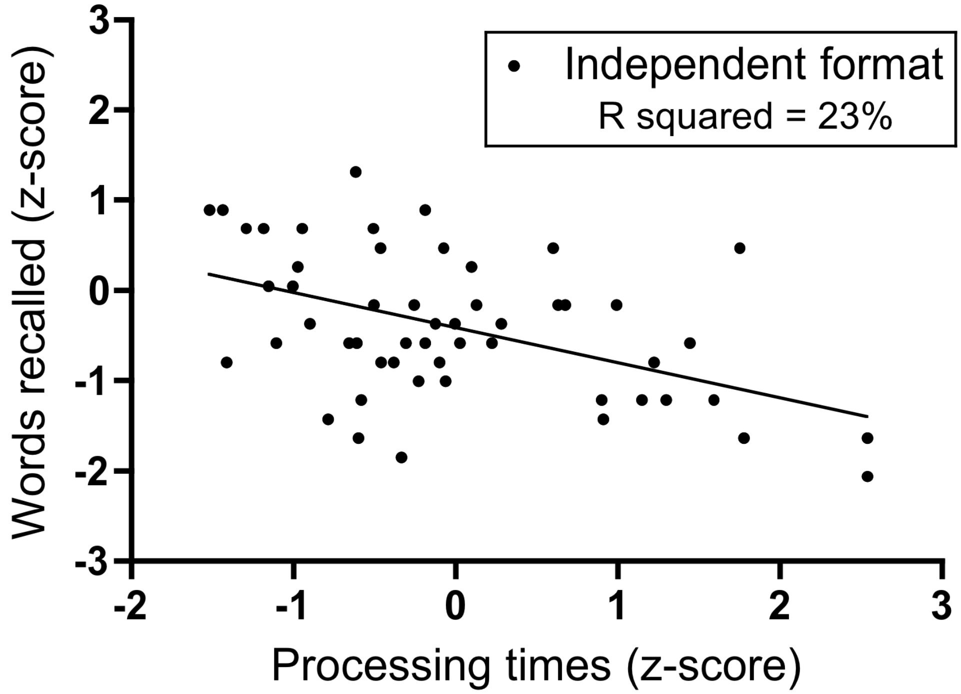
Figure 2. The relationship between time to complete sentence reading and memory recall in Experiment 1. Each variable is described as a z-score dimension. Upper panel describes the relationship for the integrated condition, the lower panel describes the independent condition. The fitted line represents the linear regression function.

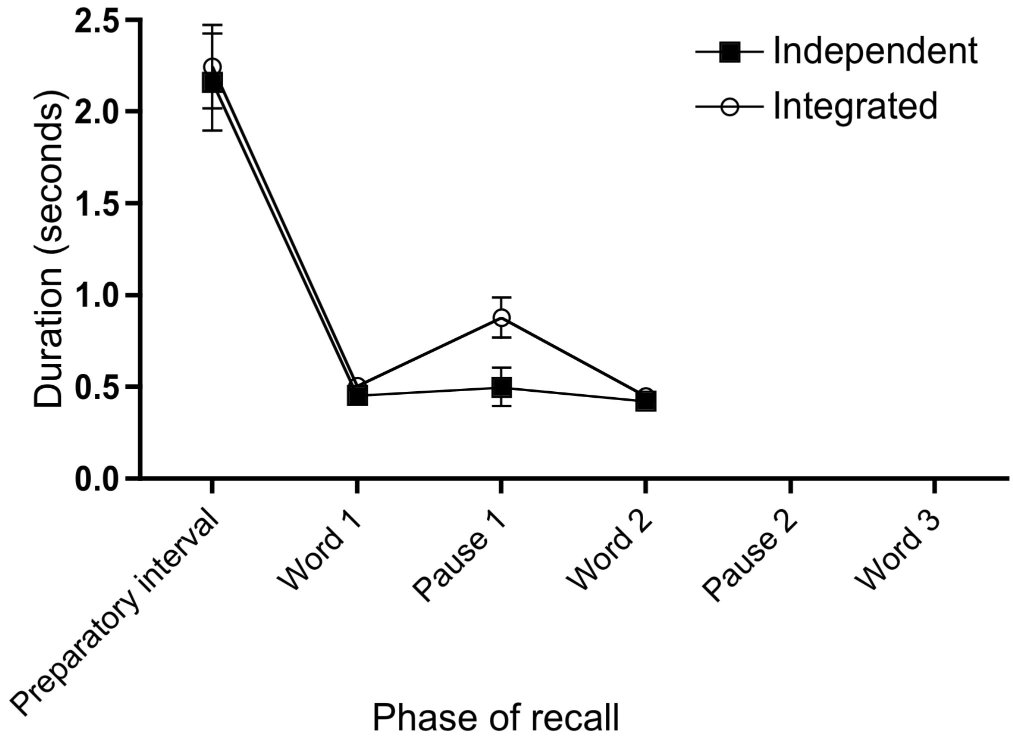
Figure 3. Mean time to recall correct sequences, as a function of reading span format and the phase of recall (the preparatory interval, recall words and interword pause[s]). Error bars indicate standard errors. Upper panel reports the recall profile from two-word sequences, the lower panel reports three-word sequences.

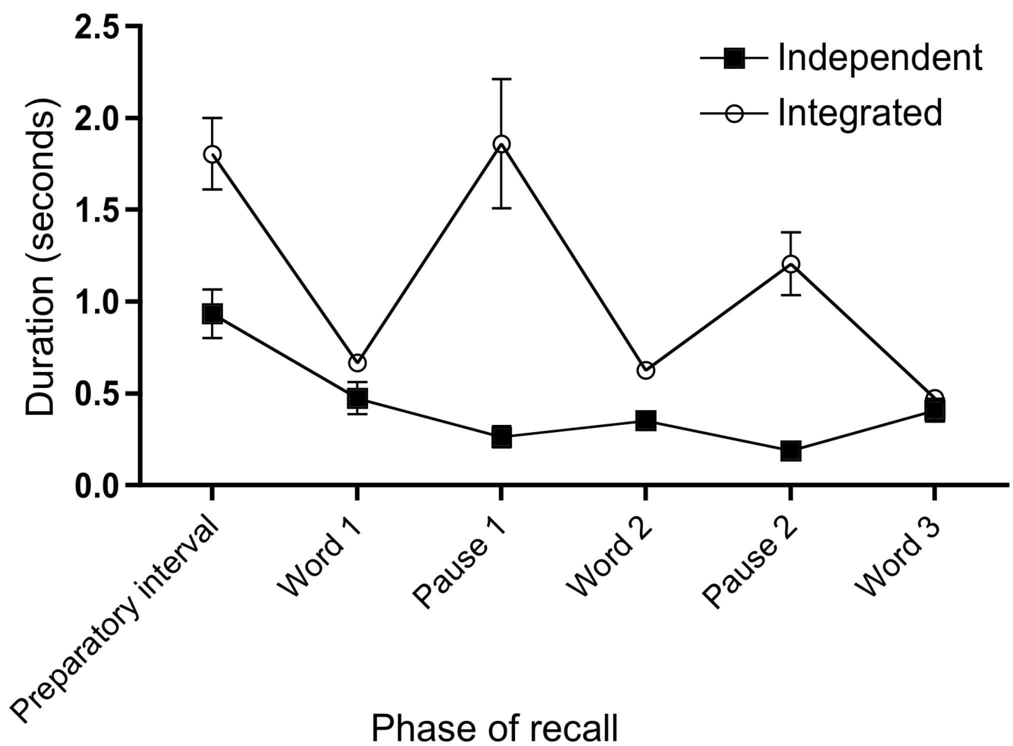

Reading span task
R squared=28.1%
Recall level (z-score)
Processing times (z-score)
4
3
2
1
0
-1
-2
-2
-1
0
1
2
3
4


Operation span task
R squared=7.3%
Recall level (z-score)
Processing times (z-score)
4
3
2
1
0
-1
-2
-2
-1
0
1
2
3
4


Integrated format
R squared=53.8%
Words recalled (z-score)
Processing times (z-score)
3
2
1
0
-1
-2
-3
-2
-1
0
1
2
3


Independent format
R squared = 23%
Words recalled (z-score)
Processing times (z-score)
3
2
1
0
-1
-2
-3
-2
-1
0
1
2
3


2.5
2.0
1.5
1.0
0.5
0.0
Duration (seconds)
Independent
Integrated
Preparatory interval
Word 1
Pause 1
Word 2
Pause 2
Word 3
Phase of recall


2.5
2.0
1.5
1.0
0.5
0.0
Duration (seconds)
Independent
Integrated
Preparatory interval
Word 1
Pause 1
Word 2
Pause 2
Word 3
Phase of recall