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Executive Control of Stimulus-driven and Goal-directed Attention in Visual Working

Memory

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Abstract

We examined the role of executive control in stimulus-driven and goal-directed attention in

visual working memory using probed recall of a series of objects, a task that allows study of

the dynamics of storage through analysis of serial position data. Experiment 1examined

whether executive control underlies goal-directed prioritization of certain items within the

sequence. While instructing participants to prioritize either the first or final item resulted in

improved recall for these items, an increase in concurrent task difficulty reduced or abolished

these gains, consistent with their dependence on executive control. Experiment 2 examined

whether executive control is involved in the disruption caused by a post-series visual

distractor (suffix). A demanding concurrent task disrupted memory for all items except the

most recent whereas a suffix disrupted only the most recent items. There was no interaction

when concurrent load and suffix were combined, suggesting that deploying selective attention

to ignore the distractor did not draw upon executive resources in our task. A final experiment

replicated the independent interfering effects of suffix and concurrent load while ruling out

possible artefacts. We discuss the results in terms of a domain-general episodic buffer in

which information is retained in a transient, limited capacity privileged state, influenced by

both stimulus-driven and goal-directed processes. The privileged state contains the most

recent environmental input together with goal-relevant representations being actively

maintained using executive resources.

     Keywords: Attention, Executive control, Visual Working Memory, Attention

Executive Control of Stimulus-driven and Goal-directed Attention in Visual Working

Memory

Steven Yantis has been a major contributor to our present understanding that selective

visual attention to objects and locations involves interactions between deliberate, goal-

directed strategies and autonomous neural responses to sensory input (Yantis, 2000; see also

Chun, Golomb and Turk-Browne, 2011; Lavie, 2010; Posner, 1980; Treisman, 1988; Yantis

& Jonides, 1990). In other work Yantis noted that models of working memory do not address

how visual attention is deployed, or indeed whether shifts of attention within working

memory and perception are mediated by the same mechanisms (Tamber-Rosenau, Esterman,

Chiu, & Yantis, 2011). This is despite a body of work that has examined these issues (see e.g.,

Awh, Vogel & Oh, 2006; D'Esposito & Postle, 2015; Gazzaley & Nobre, 2012), and is

certainly true of our own multi-component model of working memory (Baddeley & Hitch,

1974), which only went so far as assuming that deliberate strategies are controlled by a

limited capacity central executive and did not address perceptual attention. However, a

subsequent revision of the model (Baddeley, 2000) led us to investigate visual working

memory in greater depth, resulting in its elaboration to include interactions between goal-

directed strategies and visual selective attention (Allen, Baddeley & Hitch, 2014; Baddeley,

Allen& Hitch, 2011; Hu, Hitch, Baddeley, Zhang, & Allen, 2014). We briefly summarise

some of this research before going on to report new findings. Although our present focus is

upon visual working memory, we should perhaps note that we regard responsibility for the

interplay between external and internal attention as a general characteristic of working

memory in all modalities.

We use a visual working memory task in which participants view a short series of briefly presented colored shapes and are immediately probed on their memory for any one of them, using either recognition or cued recall. Sequential presentation differs from the more usual method of simultaneous presentation and has the advantage of yielding serial position (SP) curves. These curves allow fine-grained analysis of retention that help distinguish between effects of external stimulus-driven selection and those attributable to internally motivated, goal-directed control. SP curves in this task typically show a marked recency effect, sometimes combined with a modest primacy effect restricted to the first item (Allen, Baddeley & Hitch, 2006, 2014; Brown & Brockmole, 2010; Hu et al., 2014). We interpret the recency effect in terms of rapid forgetting whereby representations of more recently presented objects interfere retroactively with the representations of earlier objects in working memory, possibly through overwriting (Allen et al., 2006).

Using this paradigm, we have explored the impacts of executive control on perceptual and goal-directed attention in visual working memory using three broad manipulations. In a first series of experiments, we studied the contribution of executive processes by varying the cognitive load of a concurrent verbal task performed while encoding the visual memory items (Allen et al., 2014). Performance of a demanding concurrent task had a clear disruptive effect, impairing memory for all items apart from the very last, which was recalled at the same high level regardless of concurrent load. The absence of an effect on the final item suggests that encoding information in visual working memory is relatively automatic, while the impairment in memory for earlier items suggests that executive resources are used to offset retroactive interference (RI) and ensure these items remain active and accessible. We assume there is

little to be gained by devoting limited executive resources to maintaining the most recent item

as this is free from RI.

In a second strand, we examined the impact of perceptual selective attention by

presenting a colored shape distractor, soon (e.g., 250ms) after the presentation of to-be-

remembered items. Despite explicit instructions to ignore this 'stimulus suffix', we found it

disrupted memory for the study items (Allen, Castella, Ueno, Hitch, & Baddeley, 2015; Ueno,

Allen, Baddeley, Hitch, & Saito, 2011; Ueno, Mate, Allen, Hitch, & Baddeley, 2011). The

amount of interference depended critically on whether the suffix was drawn from the same set

as study items or a noticeably different set. Thus a 'plausible' suffix with color and shape

features from the same pool as study items caused more disruption than a suffix with

distinctive color and shape features that never appeared in study items. Furthermore, when a

plausible suffix was presented intrusion errors in cued recall tended to consist of a feature of

the suffix itself (Hu et al., 2014; Ueno, Mate et al., 2011). These intrusion errors suggest that

a plausible suffix tends to draw perceptual attention and become encoded in visual working

memory. This is further supported by the observation that a suffix with only one plausible

feature produced the same amount of interference as a suffix with two plausible features

(Ueno, Mate et al., 2011). We assume that in order to perform the memory task participants

form an attentional set for the pool of potential study items. Given that selective attention

involves feature detection (Treisman, 1988), a distractor with one or more features that match

the attentional set is likely to be selected and encoded in error. Building on this, Hu et al.

(2014, Experiment 1) found that presentation of a suffix disrupted memory for the most recent

items in a series while having no effect on earlier items, thus directly contrasting with effects

of concurrent cognitive load, which emerged on memory for all items except the last (Allen et

al., 2014). This in turn suggests a separation between the effects of perceptual selective

attention and executive control, with selective attention acting as the gateway to visual

working memory and executive control concerned with actively maintaining information once

in visual working memory.

In subsequent work (Hu et al., Experiments 2-4), we examined how the disruption

caused by the physically salient input of a suffix distractor interacted with internally-driven,

goal-directed selective attention. Specifically, we examined whether participants would be

able to strategically direct their attention towards a particular item within a sequence, by

informing them that correct recall of either the first (Experiment 2 and 4) or final (Experiment

3 and 4) item would be rewarded with more 'points' in a notional reward scheme. We found a

strong recency effect in all conditions, regardless of instructions. Over and above this

instructions to prioritize the first item substantially enhanced its recall and instructions to

prioritise the final item resulted in a small improvement to the last item's recall. Furthermore,

presentation of a post-list suffix distractor disrupted recall of the final item regardless of

whether it was prioritized but disrupted memory for the first item only when that particular

item was prioritized. We took these findings as suggesting that recent and prioritized early

items have a common status that renders them particularly vulnerable to suffix interference.

We interpreted the above outcomes as reflecting a subset of items within working

memory occupying a highly accessible but nevertheless transient privileged state. Items in

this privileged state are particularly vulnerable to overwriting when perceptual attention is

drawn to a new stimulus. This position is broadly in line with previous claims that items in

visual working memory can occupy fundamentally different states, with one or more items

being retained in a focus of attention (e.g. Cowan, 1999, 2011; Oberauer & Hein, 2002), or in

an active state capable of biasing attention selection (e.g. Olivers, Peters, Houtkamp &

Roelfsma, 2011). Our research to date suggests that this limited capacity state holds the most

recently attended perceptual input, together with other goal-relevant information we are

actively attempting to maintain (Hu et al., 2014).

However, our work so far has carried several assumptions concerning the role of

executive control in driving perceptual and goal-directed selection that are as yet untested,

and the present study aims to address some of these. Firstly, we have assumed that executive

control is critical for the goal-directed prioritization of items in visual working memory, and

further, that this is particularly the case for maintaining early items in a sequence, relative to

the final item. We test these assumptions in Experiment 1, by examining whether the ability

to prioritize the first vs. final item in a sequence is reduced by concurrent performance of an

executive-demanding verbal task. Secondly, we have assumed on the basis of earlier work

that the requirement to ignore a suffix involves some degree of executive control, even though

the encoding of a suffix distractor into visual working memory by its drawing of perceptual

attention is largely automatic (Ueno, Allen et al., 2011; Baddeley, Allen, & Hitch, 2011).

Experiments2 and 3 test this possibility by examining whether a concurrent executive load

influences the extent to which presentation of a suffix distractor disrupts recall from visual

working memory.

Experiment 1

In our first experiment we examined whether the increase in recall accuracy for a particular 'prioritized' item within a sequence is reduced or even abolished by concurrent performance of a demanding secondary task, and whether this interacts with sequence position. More specifically, we examined the effect of a concurrent load when prioritization is directed towards either the first or last item in the sequence. If the most recent item can indeed be temporarily held within the focus of attention in a relatively automatic and cost-free manner while earlier items require attentional support (Allen, et al., 2014), we would predict a substantial recency effect regardless of whether or not participants are prioritizing the final item or performing a demanding secondary task, replicating Hu et al. (2014). We also expected to replicate the finding that prioritizing the first item result in a substantial boost to its recall whereas prioritizing the most recent item would boost its recall only slightly. As in previous work we expected a concurrent task to impair recall. More critically, performance boosts deriving from prioritization should be particularly vulnerable to disruption from a demanding concurrent task if prioritizing information in visual working memory depends on resources for executive control.

We used counting aloud in twos from a randomly chosen two-digit number as the concurrent task involving high load and compared this with a low load, articulatory suppression condition in which participants simply repeated the two-digit number over and over. These two tasks are well suited for our present purpose as they are balanced for speech output and differ principally in their demands on executive processes, while disrupting any tendency to utilise verbal recoding in the visual memory task to the same extent.

Method

Participants. 20 students (aged 18-27 years, mean age 23; 12 female, 8 male) from the Northeast Normal University were tested individually and were paid for participation. All participants reported having normal color vision.

Materials. The experiment was programmed in E-prime (ver. 2.0). Stimuli were colored shapes (approximately $3° \times 3°$) viewed against a white background on a 43.2 cm PC screen from a distance of 50 cm. Sets of four study items were selected from a pool of 64 items formed by crossing eight colors (red, blue, yellow, green, sky blue, purple, gray, and black) with eight shapes (circle, diamond, triangle, cross, arrow, star, flag, and arch). Selection was random subject to the constraint that no shape or color could appear more than once among each set of four study items. The recall cue on each trial was either a color-blob or a shape-outline matching the color or shape of one of the four study items. These features were chosen randomly subject to the constraint that each of the four SPs was cued equally often by color or shape in each block of trials.

Design and procedure. A repeated measures design was implemented, manipulating concurrent load (low vs. high), strategy (primacy vs. recency), and cued SP (1-4). Concurrent load conditions were implemented in separate blocks of trials, counterbalanced between participants. Within these blocks, primacy and recency strategy instruction trials were run in separate blocks of 16 practice trials followed by 40 test trials, with half the participants taking the primacy instruction trials first for each load condition, and the other half taking the recency trials first. A short rest was inserted after 20 trials within each of these strategy blocks. Each of the four SPs was cued 10 times distributed randomly within each strategy block.

Before the experiment began participants were familiarised with the stimuli by being

shown all the potential study items with their proper names. They were instructed that their

task was to recall the name of the color (or shape) of the study item that had the same shape

(or color) as the recall cue. They were also told that different numbers of reward points were

assigned to each study item, depending on the experimental condition. In the primacy strategy

condition, participants were informed they would receive 4 points for correctly recalling the

first item and 1 point for each of the other three items. In the recency strategy condition they

were told they would get 1 point for correctly recalling any of the first three items and 4

points for the final item. Participants were informed that points were awarded with purely

notional rewards.

The procedure for each trial is illustrated in Figure 1. It began with a 500 ms warning

cross followed by a 500 ms blank screen and a 1000 ms number chosen randomly from the

range 20-99. This was followed by a 250 ms blank screen and the four study items, each

shown for 250 ms and separated by a blank interval of 250 ms. Each study item appeared at a

different vertex of a 6° × 6° invisible square centred 3° above the middle of the screen, in an

unpredictable spatial order. The final study item was followed by a 1000msblank screen and

then presentation of the recall cue, which was always shown 3° below the middle of the

screen.

INSERT FIGURE 1 ABOUT HERE

A verbal concurrent task was performed from the onset of the double digit until the onset

of the test cue. In the low load condition, participants were required to repeat aloud the two-

digit number presented at the beginning of each trial aloud. In the high load condition, they

were required to count forwards in steps of two from this number. The experimenter

monitored counting behavior to ensure compliance with instructions.

Results

Data are collapsed across cue type as there were no significant differences associated

with type of cue (*ps*>.10). As expected, the SP curves for correct responses showed a

pronounced recency effect (see Figure 2a). Prioritizing the first item led to a large boost to its

probability of recall whereas prioritizing the last item gave only a very modest boost to its

recall. These observations were principally due to performance in the low load condition (see

Figure 2b). In the high load condition recall was generally poorer (illustrated in Figure 3a)

and, importantly, strategy effects were almost absent (see Figure 2c).

A 2 (strategy) × 2 (concurrent load) × 4 (SP) ANOVA on correct responses revealed

significant effects of strategy, F (1, 19) =5.39, MSE=0.08, p<.05, η^2=0.22, load, F (1, 19)

=40.74, MSE=0.84, p<.001, η^2=0.68, and SP, F (3, 57) =61.20, MSE=3.09, p<.001, η^2=0.76.

There were two significant interactions. One was strategy × position, F (3, 57) =12.87,

MSE=0.36, p<.001, η^2=0.40, whereby the first and last items were recalled significantly more

accurately when they were prioritized, t (19) = 5.01, p<.001, and t (19) = 2.09, p=.05,

respectively, whereas other items were unaffected by strategy (Figure 2a). The three-way

interaction was also significant, F (3, 57) =3.50, MSE=0.08, p<.05, η^2=0.16, reflecting a

reduction in the strategy boost at the first SP in the primacy condition and the last SP in the

recency condition, under high concurrent load (compare Figures 3b and 3c).

INSERT FIGURES 2 AND 3 ABOUT HERE

The three-way interaction was broken down using separate 2 (load) × 2 (strategy) ANOVAs at each SP. These revealed a significant interaction at SP1, $F(1, 19) = 8.45$, $MSE = 0.19$, $p < .01$, $\eta^2 = 0.31$, reflecting a significant effect of concurrent load on recall of the first item with the primacy strategy, $t(19) = 7.48$, $p < .001$, $d = 1.24$, but not with the recency strategy, $t(19) = 1.69$, $p = .11$, $d = .45$ (see Figures 3b and 3c). The first item was recalled significantly better with the primacy strategy in both load conditions, $t(19) = 5.36$, $p < .001$, $d = 1.44$, for low load and $t(19) = 2.51$, $p < .05$, $d = .70$, for high load, though the difference was much reduced in the latter case (Figures 2b and 2c). There were no significant effects in the 2 × 2 ANOVAs for SP2 and SP3, except a main effect of load for SP2, $F(1, 19) = 7.49$, $MSE = 0.19$, $p < .05$, $\eta^2 = 0.29$. In contrast, the interaction was significant at SP4, $F(1, 19) = 5.76$, $MSE = 0.06$, $p < .05$, $\eta^2 = 0.23$, reflecting enhanced recall of the last item with the recency strategy in the low load condition, $t(19) = 3.90$, $p = .001$, $d = .88$, but not in the high load condition, $t(19) = .40$, $p = .69$, $d = .09$ (Figures 2b and 2c). Examining load effects revealed significant concurrent task interference in the recency condition, $t(19) = 2.61$, $p < .05$, $d = .81$, but not in the primacy condition, $t(19) = .42$, $p = .68$, $d = .09$ (Figures 3b and 3c).

Errors were categorised as within-sequence confusions (i.e., the shape or color one of the other items presented on the trial in question) or intrusions (i.e., a shape or color that was not presented on that trial). Omissions were rare in all the experiments reported here (<0.01%). Overall, within-sequence confusions were about twice as frequent as intrusion errors ($M = 40\%$ vs $M = 21\%$).

Discussion

The results replicate the pattern of increased cognitive load effects at early rather than later sequence positions (Allen et al., 2014), and the increase in the accuracy of recalling primacy or recency items when they were prioritized through instructions (Hu et al., 2014). The way these effects interact casts new light on visual working memory and attentional control. As predicted, prioritization effects at both the first and final sequence positions were substantially reduced when participants engaged in a more demanding concurrent verbal task, suggesting a key role for executive control. Furthermore, the form of the interaction between concurrent load and strategic priority across SPs was consistent with our earlier evidence that executive resources are more important for actively maintaining earlier items than the most recent item. Thus primacy was only observed when instructions to prioritize the first item were combined with a relatively easy concurrent task whereas recency was present regardless of strategy and the difficulty of the concurrent task. The further observation that recency instructions resulted in a modest boost to recall of the final item that disappeared when performing a demanding concurrent task is consistent with recency as a predominantly automatic effect that can nevertheless be supplemented by goal-directed executive processes. Finally, the interfering effect of concurrent load at the final position implies participants complied with the instruction to maintain verbal task performance throughout presentation of the study items.

Having provided firm evidence that resources for executive control are required for goal-directed attention in visual working memory, we turned next to examine whether these same resources are required for shifts of stimulus-driven attention in visual working memory. This would bear on the answer to Steven Yantis and colleagues' question whether common

mechanisms underpin shifts of attention in working memory and perception (Tamber-Rosenau et al., 2011).

Experiment 2

Our next experiment was designed to explore the role of executive control resources in mediating the impacts of stimulus-driven perceptual selective attention on visual working memory. Firstly, we sought to confirm within a single cued recall experiment that manipulations of verbal concurrent task difficulty and the presence or absence of a 'to-be-ignored' visual stimulus suffix impact on earlier and later sequence positions respectively (Allen et al., 2014; Hu et al., 2014). Secondly, and crucially, we examined whether these factors would interact, in line with the suggestion that ignoring a suffix depends on executive control (Baddeley et al., 2011; Ueno, Allen, et al., 2011), and evidence from other visual tasks that the ability to resist distracting stimuli is impaired when cognitive load is high (e.g. Lavie, 2010). If this were the case, we would expect to find an increase in the extent to which a suffix interferes with recall when performing a more demanding concurrent task. We used a stronger manipulation of load than in Experiment 1 in that the more demanding concurrent task involved counting backwards rather than forwards by twos.

Method

Participants. Twenty students (aged 19-32 years, mean age 23, 11 female, 9 male) from the University of York were tested individually. All participants reported having normal color vision and were paid or given course credit.

Materials. Stimuli were those used in Experiment 1 with the exception that on half

the trials the study items were followed by a suffix. The suffix was selected randomly from

the pool of 64 experimental items subject to the constraint that neither its color nor shape

matched any of the study items for that trial.

Design and Procedure. A factorial repeated measures design was used testing all

combinations of concurrent load (low vs. high), suffix (present vs. absent) and cued SP (1-4).

The trial procedure was closely based on Experiment 1, the only change being what happened

after presentation of the final target item. On half the trials a visual suffix was presented.

These trials consisted of a 250 ms blank screen followed by a 250 msec presentation of the

suffix at the center of the invisible square, followed by a 500 msec blank screen. This was

followed by the recall cue, presented 3° below the middle of the screen, as before. To help

participants differentiate the suffix from the preceding study items it was accompanied by a

250 ms auditory beep. On no-suffix trials the final study item was followed by a 1000ms

blank screen followed by presentation of the recall cue. An auditory beep was played during

the blank screen with the same timing as suffix trials, Participants were instructed to respond

to the recall cue as before and to ignore the suffix. Unlike the previous experiment there were

no instructions to prioritize particular study items.

As in Experiment 1, a verbal concurrent task was performed from the onset of the

double-digit number until the onset of the test cue. The only difference was that participants

were required to count backwards in twos from this number (rather than forwards) in the high

load condition.

The load conditions were performed in separate blocks of trials with order

counterbalanced across participants. Each load condition consisted of a block of 16 practice

trials and 4 blocks of 20 experimental trials with short rests between blocks. The various

permutations of suffix condition (2), cue type (2) and SP of the cued item (4) were randomly

ordered within each block.

Results

As before, data are collapsed over the shape- and color-cue conditions, there being no

significant differences associated with type of cue ($ps> .10$).

As expected the SP curves showed recency over all items except the first, for which there

was a small primacy effect. Figure 4 illustrates this and shows also that concurrent backward

counting impaired memory for early items but not the last. In contrast, presentation of a suffix

disrupted memory for the most recent items but had no effect on memory for earlier items, as

shown in Figure 5. A 2 (concurrent load) × 2 (suffix condition) × 4 (SP) repeated measures

ANOVA revealed significant main effects of load, $F (1, 19) =49.82$, MSE=1.00, $p<.001$, η^2

=.72, suffix, $F (1, 19) =46.38$, MSE=0.89, $p<.001$, $\eta^2 =.71$, and SP, $F (3, 19) =43.70$,

MSE=1.90, $p<.001$, $\eta^2 =.70$. There were just two significant interactions. One was load × SP,

$F (3, 57) =4.23$, $MSE=0.11$, $p<.01$, $\eta^2 =.18$, reflecting significant effects of load at SPs 1, 2

and 3, $t (19) = 4.46$, 4.47 and 3.92, $ps<.001$ and $p=.001$, respectively but no reliable

difference at SP 4, $t (19) < 1$ (Figure 4). The second significant interaction was suffix × SP, F

$(3, 57) = 10.45$, $MSE= 0.23$, $p<.001$, $\eta^2 = .36$, reflecting significant suffix interference at SPs

3 and 4, $t (19) =4.53$, $p<.001$and $t (19) =7.46$, $p<.001$ respectively, but no effect at SPs 1 and

2, t < 1 in each case (Figure 5). Importantly, neither the load by suffix interaction nor the

three-way interaction were significant, ps >.10.

INSERT FIGURES 4 & 5 ABOUT HERE

Table 1 summarises the means for the load by suffix interaction in the final column and

shows that there was slightly more suffix interference in the high load condition. We re-

examined the interaction using data from SPs 3 & 4 combined as these are the items sensitive

to suffix interference. The interaction remained non-significant in this more focused analysis,

$F(1,19) = 0.35$, MES=0.01, p=0.56, η^2=0.02. We assessed the strength of support for the null

hypothesis by means of a Bayesian analysis of the interaction comparison, using JASP

software (Love et al., 2015). This gave a Bayes factor of 0.41, indicating a likelihood ratio of

2.4:1 in favor of the null hypothesis relative to the experimental hypothesis.

INSERT TABLE 1 ABOUT HERE

As in Experiment 1 errors were categorised as within-sequence confusions (i.e., recalling

the shape or color of another study item) or intrusions (i.e., recalling a shape or color from

outside the study set). Overall, within-sequence confusions were about twice as frequent as

intrusions (M = 41% vs M = 21%), as in Experiment 1. In addition, errors of recalling a

feature of the suffix formed 45% and 47% of intrusions in the low and high load conditions

respectively, i.e. approximately twice the chance rate of 25%.

Discussion

The results confirm the robustness of our previous observations of contrasting SP effects

of a concurrent load and a post-stimulus suffix on visual working memory. Thus, an irrelevant

executive load disrupted memory for all items except the most recent, consistent with Allen et

al. (2014), whereas an irrelevant suffix disrupted memory for only the most recent items,

consistent with Hu et al., 2014 (Experiment 1). We also confirmed the observation that

presentation of a suffix tended to induce errors of recalling one of its features, consistent with

our view that a suffix interferes by drawing perceptual attention.

We note that the suffix interference we find here is unlikely to reflect overwriting in a

sensory store (Crowder & Morton, 1969) or perceptual grouping (Kahneman & Henik, 1977)

as it extends to the first study item when prioritization instructions emphasise that item (Hu et

al., 2014, Experiments 3 &4).

The important new finding is that the amount of suffix interference was independent of

concurrent load. Given previous evidence that the ability to ignore perceptual distractors is

impaired under conditions of high cognitive load (Lavie, 2005; 2010) we had expected an

increase in the amount of suffix interference when performing a demanding concurrent task.

This argues against our earlier suggestion that attending selectively to a series of target items

and rejecting a subsequent distractor places some demands on executive resources (Baddeley

et al., 2011; Ueno, Allen et al., 2011). However, the present results alone are not decisive

given that the Bayesian analysis provided only weak support for concluding that suffix

interference is independent of concurrent cognitive load.

A further concern is that the experimental procedure may have allowed participants to

form a strong temporal expectation of when the suffix and recall cue would occur, making it a

useful strategy to stop repeating numbers aloud before this critical time-window. If so this

could potentially explain the lack of increase in suffix interference with the more demanding

concurrent task (see Footnote). We think it unlikely participants did stop counting at the end

of the list as they were monitored by the experimenter to ensure compliance. In addition

Experiment 1 provides indirect evidence that participants continued counting throughout the

list in that counting impaired memory for the last item when they were instructed to prioritize

this item. However, it would clearly be more convincing if we could show objectively that

participants maintained counting throughout presentation of the study items and thereby rule

out the possibility that the absence of an interaction between suffix and load might reflect any

artefact associated with being able to anticipate when their presentation would end.

Experiment 3

Our final experiment re-examined the question of whether ignoring a visual suffix

depends on resources for executive control using dual-task methodology but with two

substantial changes from Experiment 2. First, we monitored the counting task to ensure

participants did not stop repeating numbers as the study list came to an end. Second, we made

it difficult for participants to form a strong temporal expectation about the end of the study list

by varying the number of study items.

Participants were given an initial practice session in which equal numbers of lists

contained 3, 4 or 5 study items, the number varying unpredictably from trial to trial. To avoid

ceiling and floor effects we collected recall data for list length 4 only and therefore the

majority of the experimental trials were of this length (80% involved 4 study items, 10% 3

items and 10% 5 items, again varying unpredictably from trial to trial).

We measured counting performance in terms of number of steps completed and

accuracy. This gave us the opportunity to examine whether the number of steps increased

linearly with list length, as would be expected if participants maintained an even counting

rate.

Method

   Participants. Twenty students (aged 18-30 years, mean age 23, 14 female, 6 male) from

the Northeast Normal University of China were tested individually. All participants reported

having normal color vision and were paid for their assistance.

   Materials. Stimuli were the same as in Experiment 2 except that lists contained 3, 4 or 5

study items.

   Design and procedure. A factorial repeated measures design was used testing all

combinations of concurrent load (low vs. high), suffix (present vs. absent) and cued SP (1-4).

   The procedure was the same as Experiment 2 except that sequence length varied

randomly from 3 to 5 across trials, and study items appeared at the vertices of an

invisible regular pentagon (appropriate $6°\times6°$) in a predictable clockwise order. The bottom

edge of the invisible pentagon paralleled to the x-axis and the first study item appeared at its

peak.

   There were 4 blocks of 25 experimental trials (10 for list length 3, 80 for list length 4 and

10 for list length 5) for each load condition. The 10 trials per load condition at lengths 3 and 5

were randomly selected (without replacement) from the 12/20 combinations of probe type (2)

$\times$suffix (2) $\times$ SP (3/5). Memory data for these trials were not analysed.

   The load conditions were the same as in Experiment 2 and were performed in successive

blocks of trials in counterbalanced order. Participants were required to continue speaking until

the onset of the probe for each trial and their performance was noted by the experimenter.

The experimental trials for each load condition were preceded by 12 practice trials. These

comprised an equal number of trials at each of the three list lengths in an unpredictable order

to generate a strong expectation of variable list length.

Results

Accuracy in the backward counting task was high with a mean error rate of less than 5%.

The mean numbers of steps completed per trial were 3.66±0.20 for list length 3, 3.94±0.21

for length 4 and 4.22±0.24 for length 5. A 2(suffix) × 3(list length) ANOVA on these data

showed a significant effect of list length, $F(2, 38) = 43.58$, MSE=3.08, $p<.001$, $\eta^2 = .70$, no

effect of the suffix and no interaction, $ps> .10$ in each case. It is noteworthy that the increase

in number of steps completed from list lengths 3 to 4 and from 4 to 5 were identical,

suggesting participants maintained an even rate of counting throughout lists.

The recall data are once again collapsed over the shape- and color-cue conditions, there

being no significant differences associated with type of cue ($ps> .09$). In all four conditions

SP curves were characterised by recency with no primacy (see Figure 6). Figure 6 shows that

current backward counting impaired memory for all items in a sequence whereas, in contrast,

presentation of a suffix disrupted memory for the most recent items but had no effect on

memory for earlier items.

A 2 (concurrent load) × 2 (suffix condition) × 4 (SP) repeated measures ANOVA

revealed significant main effects of load, $F (1, 19) = 44.35$, MSE=0.90, $p<.001$, $\eta^2 = .70$,

suffix, $F (1, 19) = 58.36$, MSE=0.99, $p<.001$, $\eta^2 = .75$, and SP, $F (3, 19) = 39.59$, MSE=1.42,

$p<.001$, $\eta^2 = .68$. There was only one significant interaction. That was suffix × SP, $F (3, 57) =$

18.06, $MSE= 0.37$, $p<.001$, $\eta^2= .49$, reflecting significant suffix interference at SPs 3 and 4, t

(19) =3.37 and 8.37, $p<.01$ and $p<.001$, respectively, but no effect at SPs 1and 2, $ps \geq .09$

(Figure 6b).The load × suffix interaction and the load × SP interaction were both non-

significant, F (1, 19) = 0.63, MSE= 0.01, p=.44, η^2= .03, and F (3, 57) = 0.93, MSE= 0.03,

p=.43, η^2= .05, respectively, as was the three-way interaction, F (3, 57) = 0.19, MSE= 0.01,

p=.90, η^2= .01

Table 2 shows the means for the load by suffix interaction of Experiment 3 in the final

column. In order to run a more powerful test for the load by suffix interaction, data from the

first two items were discarded and data for the last two items was combined, as in the analysis

of Experiment 2. A 2 (load) × 2 (suffix condition) ANOVA on these data showed significant

main effects of load, F (1, 19) =19.68, MSE=0.36, $p<.001$, η^2 =.51, and suffix, F (1, 19)

=70.79, MSE=0.83, $p<.001$, η^2 =.79. However, once again the load by suffix interaction was

non-significant, F (1, 19) =1.00, MSE=0.01, p=.33, η^2 =.05, and the small difference in the

size of the suffix effect was in the opposite direction to that predicted. The Bayes factor for

the interaction was 0.13, indicating moderate support for the null hypothesis with a likelihood

ratio of 7.5:1.

INSERT TABLE 2 ABOUT HERE

As in Experiments 1 and 2, errors in recall were classified as either within-sequence

confusions or extra-list intrusions. Once again, extra-list intrusions were much more frequent

than within-list confusions (M = 43% vs M = 26%) and a common type of intrusion consisted

of recalling a feature of the suffix, accounting for50% and 58% of intrusions in the low and

high load conditions respectively, t(19)=1.27, p=0.22.

Discussion

The results confirmed Experiment 2 in showing no increase in suffix interference when

performing a demanding concurrent task. Replication of this outcome with a changed

procedure suggests that the absence of the interaction in Experiment 2 was not an artefact of

participants being able to form a temporal expectation for when each study sequence would

end and tending to stop counting. Moreover, when Experiments 2 and 3 are considered

together by combining the independent Bayes factors, we see that support for the null

hypothesis is substantial (with a likelihood ratio of 20:1). This suggests separate effects

of cognitive load and suffix interference on visual working memory, whereby executive

resources are not involved in ignoring a visual distractor presented immediately after

encoding study items.

There were, however, some interesting differences in outcome compared with

Experiment 2. Thus, while the recency and suffix effects had the same form, backwards

counting disrupted memory for all study items rather than earlier items only, and the modest

primacy effect observed previously was no longer present. The reduction is primacy was not

unexpected as Crowder (1969) found a reduction in primacy with unpredictable list length in

verbal short-term memory, which he attributed to a change in rehearsal strategies. We suggest

that some analogous change in visual memorization strategies underpins the difference in

outcomes when list length was predictable (Experiment 2) or unpredictable (Experiment 3).

For example, the variation of dual-task interference with SP reported by Allen et al. (2014)

suggests that participants typically remain passive for the last item, relying on automatic

encoding. We assume this was the case with predictable list length in Experiment 2. However,

when list length is unpredictable it is plausible to assume participants will be less confident of

remaining passive for the fourth item in each trial as it may not necessarily the last. We

already know from Experiment 1 that they can deploy executive resources to boost recall of

the last item when instructed to prioritize it. If participants were to have done so

spontaneously in Experiment 3, this would account for the extension of dual-task interference

to the most recent item. Furthermore, this strategy would take executive resources away

from actively maintaining earlier items and could therefore account for the reduction

in primacy, too.

General Discussion

The present experiments examined how executive control might contribute to two

different aspects of attention in the operation of visual working memory, namely stimulus-

driven perceptual selective attention and internally-driven, goal-directed control. We used a

task in which participants were probed for recall of a single item from a short series. This task

provides information about SP effects that have already proved useful in identifying separate

and contrasting roles of perceptual selective attention, goal-directed prioritization, and

executive control (Allen et al., 2014; Hu et al., 2014). The present experiments replicated and

extended outcomes from these earlier studies, and will be discussed in turn.

Experiment 1 demonstrated that particular items within a sequence can be prioritized

to enhance their recall, but that this process is dependent on the availability of executive

support. Earlier items in a sequence are reliant on executive support to remain accessible,

while the most recently encountered item tends to be automatically accessible (though this

can be supplemented via executive support). How might we characterise the nature of the

executive control mechanism that drives this active prioritization in working memory? One

possibility is that executive control serves a general role in overseeing effective item

rehearsal, ensuring that more specialised resources (e.g. space-based and object-oriented

attention, see Shen, Huang, & Gao, 2015) are appropriately allocated. Along similar lines,

executive control may support a process of active and sustained visualization (e.g. Phillips,

1983) that serves to maintain older items in the face of RI from incoming stimuli.

Alternatively, the contribution of executive control might reflect a form of attentional

refreshing (e.g. Barrouillet & Camos, 2015; Barrouillet, Bernadin, Portrat, Vergauwe,&

Camos, 2007; Hollingworth & Maxcey-Richard, 2013; Souza, Rerko, & Oberauer, 2015), a

process akin to reactivation of memory items through scanning (Cowan, 1992; Vergauwe &

Cowan, 2015) or recirculation through the focus of attention (Cowan, 1995), that is likely

executive-based and distinct from verbal rehearsal (Camos, Lagner, & Barrouillet, 2009; Raye

et al., 2007). Regardless of the specific nature of this process, it is typically more important

for earlier sequence items, particularly when they are identified as a goal-relevant priority.

The increased attentional demands imposed by our concurrent task manipulation would then

mean that participants were less able to keep these items active.

Experiments 2 and 3 indicated that an external stimulus suffix and a demanding

concurrent task have separate effects on visual working memory. Thus, having to ignore a

suffix distractor interferes with memory for recent items only whereas a concurrent cognitive

load disrupts memory for earlier items (Experiment 2) or all items (Experiment 3), depending

on task context. In both experiments the size of the suffix effect was independent of cognitive

load, suggesting that ignoring the suffix distractor involves automatic, stimulus-driven

perceptual selection. While previous work has suggested that attentional capture is subject to

a degree of top-down modulation (e.g. Yantis and Jonides, 1990), such modulation does not

appear to be dependent on availability of resources for executive control in the present

context. This apparent independence of perceptual distractor interference and executive

control runs counter to cognitive load theory (Lavie, 2005; 2010), and may reflect the serial

presentation of a single distractor after target items in the present task. Future work could

usefully examine the extent to which distractors encountered simultaneously alongside targets

require executive support for their exclusion.

In order to begin to explain the dynamics of storage we, like others, have found it

useful to assume that information in visual working memory can occupy different

states(Cowan, 2011; Hollingworth & Hwang, 2013; Lewis-Peacock, Drysdale, Oberauer, &

Postle, 2012; Oberauer & Hein, 2012; Olivers et al., 2011). We assume that a limited amount

of information can be held in a *privileged state* whereby it is readily available and yet

unstable and highly vulnerable to interference (Hu et al., 2014). As each item in a sequence is

encountered, it is automatically encoded and temporarily held within this state. A to-be-

ignored suffix distractor may also sometimes gain access by drawing perceptual selective

attention. In each case, this environmental input is likely to interfere with and displace earlier

items already being held. The current study indicates that participants can actively prioritize

goal-relevant items for retention, in a process that is executive-dependent. However, this does

not prevent the automatic consolidation of subsequently attended items, even if these are less

goal-relevant (see Maxcey-Richard & Hollingworth, 2013, for a similar conclusion in the

context of scene memory). Thus, some information is retained in the privileged state through

the deployment of executive control, while the most recent item is privileged relatively

automatically. We identify the privileged state with a modality-general episodic buffer that

can be accessed either actively, using executive resources, or passively, via the visual short-

term store (Allen et al., 2014; Baddeley et al., 2011; Hu et al., 2014). While recognising that

this tentative account leaves many questions open, it may nevertheless have some value in

encouraging more integration between research on selective attention and on working

memory, and in suggesting a dynamic structure for working memory that may extend to non-

visual modalities.

We began with the observation that models of working memory do not say whether

shifts of attention within working memory are mediated by the same mechanisms as in

perception (Tamber-Rosenau et al., 2011). We assumed that the success with which items are

initially perceived and encoded into WM is likely to be determined by a combination of

stimulus-driven attentional selection and top-down biases (Desimone & Duncan, 1995;

Serences &Yantis 2006). Our results suggest that to-be-ignored external stimuli (i.e. the suffix

in Experiments 2 and 3) take advantage of this, often being automatically encoded into WM

and disrupting target recall. It appears that when external attention is inadvertently drawn to a

stimulus this is independent of executive control, at least under the serial presentation

conditions of our experiments. In contrast, deliberately maintaining items in an active and

accessible state through visualization or attentional refreshing does appear to require

substantial executive support (Experiment 1). Thus, what is accessible in working memory

reflects both top-down, goal-driven priorities under executive control and the results of

automatic perceptual selection from the external environment. The present experiments

demonstrate how the impacts on visual working memory of these different forms of

attentional selection and control can be distinguished and manipulated, and thus move

towards addressing the theoretical gap identified by Steven Yantis between models of

working memory and visual attention.

Footnote

We are grateful to an anonymous reviewer for pointing this out.

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Table 1. Mean proportion of correct responses (and SE) as a function of concurrent task,

suffix and serial position in Experiment 2.

Concurrent Load	Suffix condition	SP1	SP2	SP3	SP4	Grand Mean
Low load	No suffix	0.39±0.05	0.34±0.05	0.47±0.04	0.71±0.04	0.48±0.03
Low load	Suffix	0.43±0.04	0.32±0.04	0.32±0.05	0.50±0.06	0.39±0.03
High load	No suffix	0.28±0.04	0.18±0.03	0.34±0.04	0.74±0.03	0.39±0.02
High load	Suffix	0.20±0.03	0.16±0.02	0.21±0.03	0.46±0.04	0.26±0.02

Table 2. Mean proportion of correct responses (and SE) as a function of concurrent task,

suffix and serial position in Experiment 3

Concurrent Load	Suffix condition	SP1	SP2	SP3	SP4	Grand Mean
Low load	No suffix	0.26 ± 0.03	0.30 ± 0.05	0.40 ± 0.05	0.75 ± 0.04	0.43 ± 0.03
Low load	Suffix	0.23 ± 0.03	0.29 ± 0.04	0.28 ± 0.04	0.42 ± 0.04	0.31 ± 0.02
High load	No suffix	0.19 ± 0.03	0.21 ± 0.03	0.27 ± 0.04	0.57 ± 0.05	0.31 ± 0.02
High load	Suffix	0.15 ± 0.03	0.21 ± 0.03	0.19 ± 0.04	0.29 ± 0.05	0.21 ± 0.02
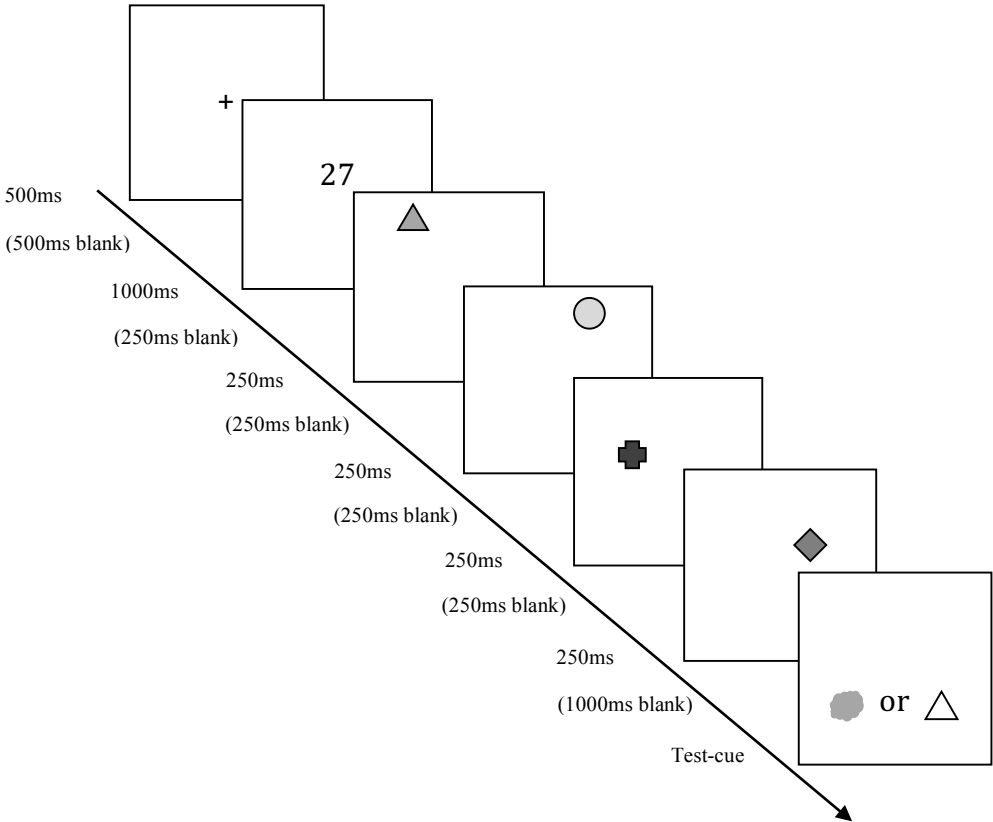
Figure 1. Time course on each trial in Experiment 1
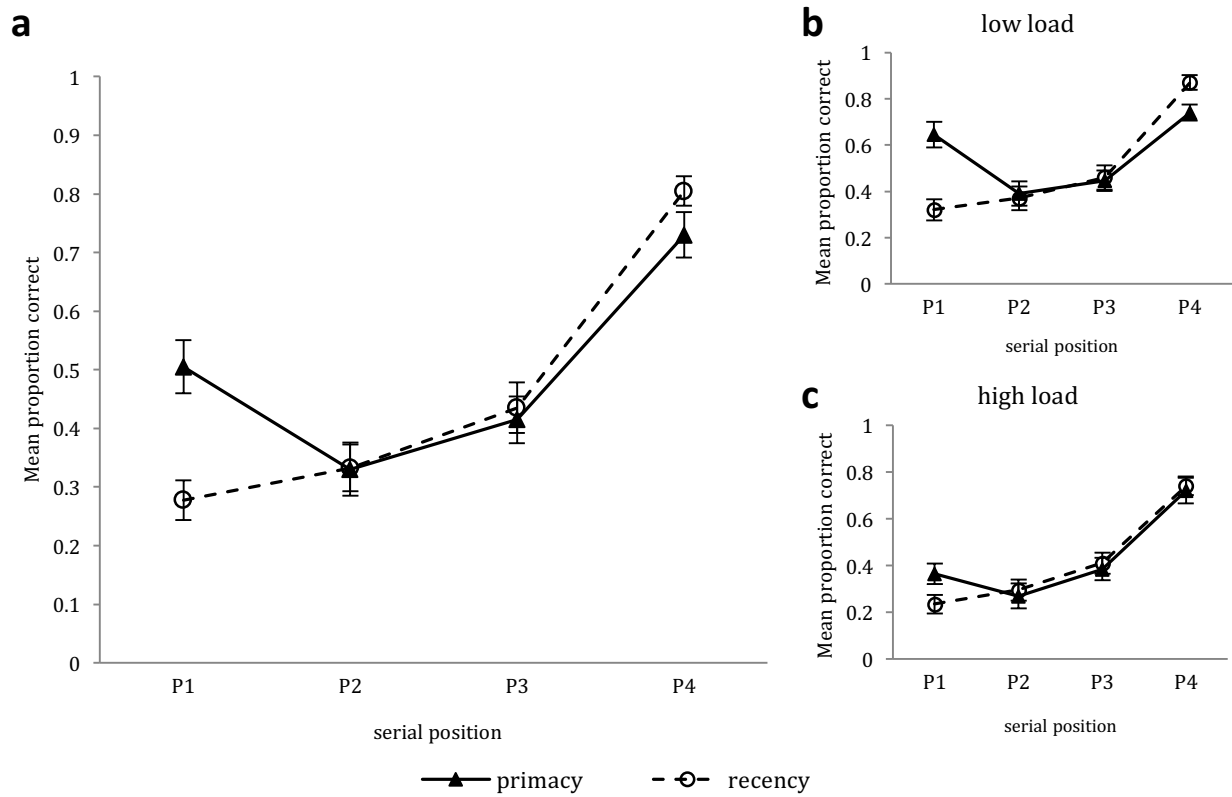
Figure 2. a) Mean proportion of correct responses for each strategy condition in Experiment 1.

b) Effect of strategy in the low load condition. c) Effect of strategy in the high load condition.
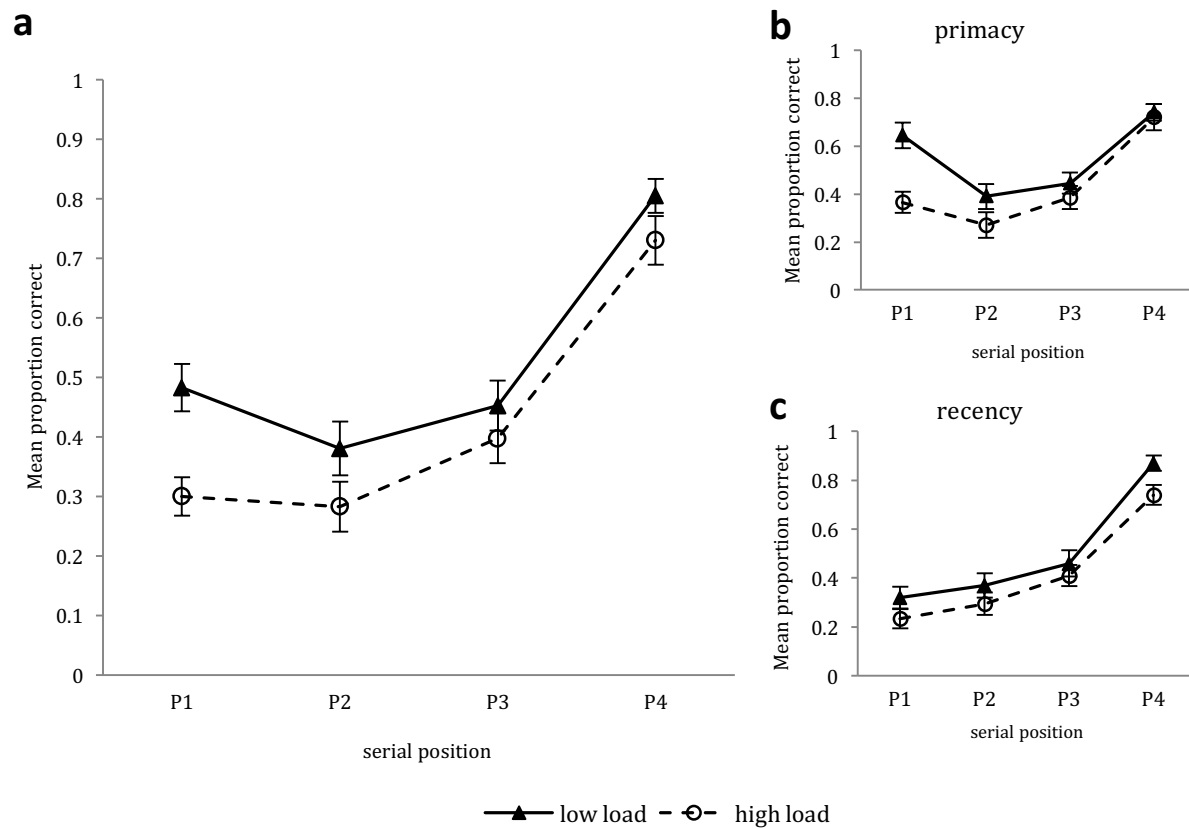
Error bars denote standard error.

Figure 3. a) Mean proportion of correct responsesfor each load condition in

Experiment 1. b) Effect of load with primacy instructions. c) Effect of load with
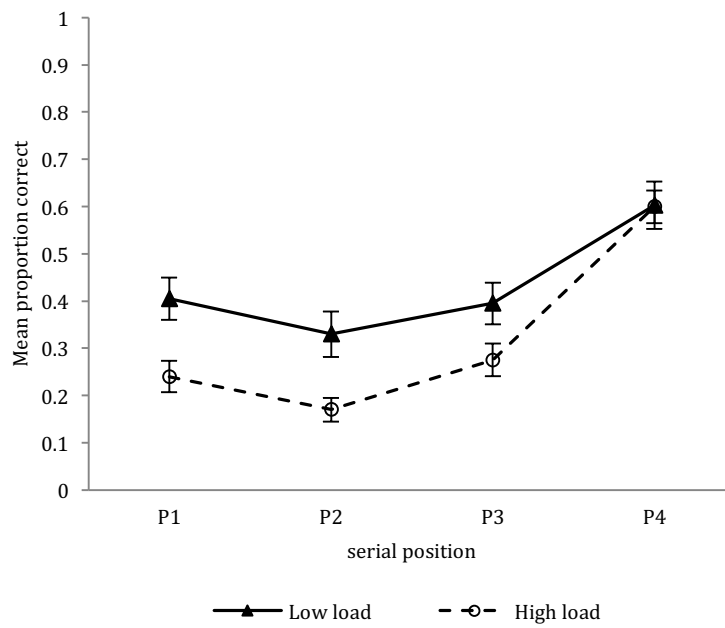
recency instructions. Error bars denote standard error.

Figure 4. Mean proportion of correct responses as a function of concurrent load and SP in Experiment 2. Error bars denote standard error.
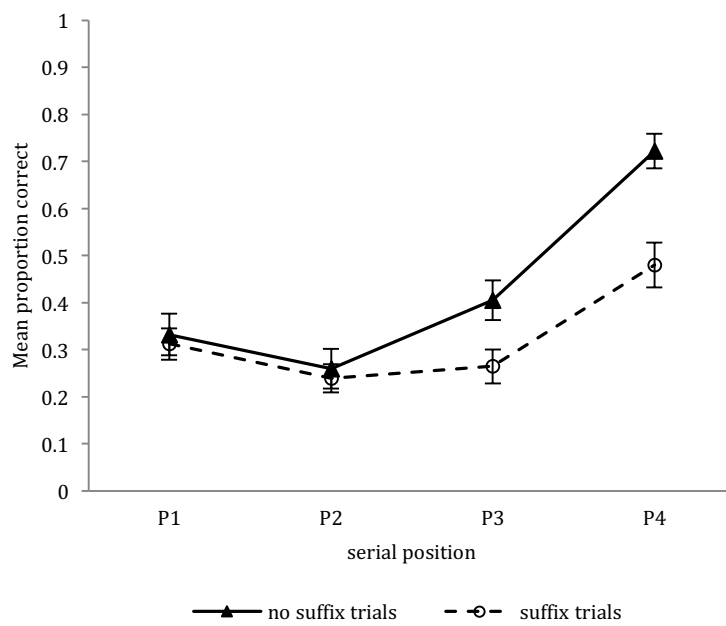
Figure 5. Mean proportion of correct responses in each suffix condition as a function of SP in Experiment 2. Error bars denote standard error.
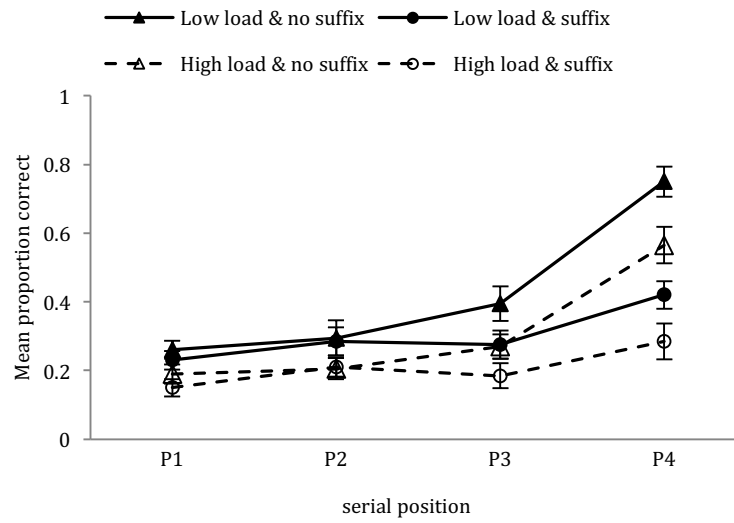
Figure 6. Mean proportion of correct responses as a function of concurrent task, suffix and serial position in Experiment 3. Error bars denote standard error.