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Parallel consolidation into visual working memory results in reduced precision representations

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ABSTRACT

Information can be consolidated into visual working memory in parallel, i.e. two items can be consolidated in the same time required to consolidate one. However, while motion direction items consolidated in parallel are encoded at a reduced precision, no such reduction has been reported for colour. Here we examine two possible explanations for the inconsistency between the phenomena associated with consolidating these features in parallel: *i*) that reduced precision can only be detected when more than two colour items are consolidated in parallel, or *ii*) that the exposure duration used in previous studies was too long, allowing observers serially consolidate items. Our results show that (like motion direction) colour items consolidated in parallel are encoded at a reduced precision and the critical feature for detecting this phenomenon is the exposure duration. Furthermore, we demonstrate that this process is limited to two items. These findings indicate a general principle of consolidation into visual working memory, that is, a trade-off between the number of items consolidated in parallel and the precision at which they are encoded.

1. Introduction

A fraction of the information within sensory memory can be consolidated into visual working memory (VWM) (Cowan, 2001; Phillips, 1974). Once consolidated, information can be maintained, manipulated, or replaced with new information, underpinning behaviours ranging from perception, to problem solving and motor control. While storage capacity has traditionally been the major focus of research, recent interest has focused on consolidation/encoding; defined here as the process of transforming a brief perceptual representation into a durable VWM representation that can endure new sensory inputs (Vogel, Woodman, & Luck, 2006).

With regard to consolidation, the main issues of interest have been a) whether parallel consolidation is possible, and b) if there is a cost associated with this process, i.e. a loss of precision. Initial evidence for these issues was based on studies using colour and orientation (Becker, Miller, & Liu, 2013; Mance, Becker, & Liu, 2012). In these studies, observers are briefly presented with multiple items, which differ along a feature dimension, and asked to indicate either the presence/absence of an item in the array or – in later experiments – the identity of a target item on a continuous measure. Critically, the duration that the items are presented is individually predetermined to match the minimum duration needed to consolidate a single item. Items are presented either sequentially or simultaneously, and performance on the task is compared between conditions. The rational being that if items cannot be consolidated in parallel, observers will only have sufficient time to process one of the items presented simultaneously, but all items presented sequentially. Using this method, it was found that colour can be consolidated in parallel (Mance, Becker, & Liu, 2012), with no apparent loss in precision (Miller, Becker, & Liu, 2014), while evidence suggested orientation may be limited to serial processing (Becker, Miller, & Liu, 2013; Liu & Becker, 2013).

In contrast, we recently demonstrated that motion direction can also be consolidated in parallel (Rideaux, Apthorp, & Edwards, 2015), and that there is a reduction in the precision of encoded items (Rideaux & Edwards, 2016). Does this mean that these features are processed by consolidation mechanisms with distinct properties?

Miller et al. (2014) supported this possibility, proposing that colour is processed more categorically than other features, i.e. orientation and direction, and is therefore less susceptible to precision loss. Another possibility is that the there is a reduction in precision associated with consolidating colour in parallel; thus, the same model can account for parallel consolidation of both colour and motion direction. For instance, the original experiment – using colour – may not have distributed resources (engaged during consolidation) across a sufficiently high enough number of items to detect any noticeable difference in

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precision (Miller et al., 2014). Thus, while a reduction in precision can be detected between serial and parallel consolidation of only two items defined by motion direction, the consolidation resources may not be sufficiently distributed by parallel consolidation of only two colour stimuli to present a noticeable reduction in precision. One way to examine this possibility is to determine whether precision is lost when resources are distributed even further, i.e. attempting to consolidate three colours in parallel. However, it remains unclear whether parallel consolidation of three items is possible. Mance et al. (2012) found some evidence for a parallel consolidation capacity of two for colour stimuli using a matching task; however, the authors conceded that this may have been underestimated due to selectively disadvantaging performance in the simultaneous presentation condition with longer retention intervals (than in the sequential condition).

Alternatively, another way to account for the putative failure to detect a reduction in precision is that the exposure duration employed by Miller et al. (2014) may have allowed observers to employ a serial strategy that does not influence precision, rather than forcing them to engage in parallel consolidation. The authors used a fixed exposure duration for all observers, derived from the mean of tailored exposure durations found in a previous experiment. This critical value was established in the previous experiment by determining the minimum exposure duration for which observers could consolidate two items serially. By requiring observers to encode, store, and retrieve an additional second item, the task difficulty was increased, and as a result, likely overestimated the actual duration required to consolidate a single item. One could argue that the same method was also used to establish the threshold exposure duration for orientation and motion direction (where a reduction in precision associated with parallel consolidation was found), thus supporting its validity. However, colour appears to be consolidated in about half the duration required for motion direction (Rideaux & Edwards, 2014; Mance et al., 2012; Rideaux & Edwards, 2016; Rideaux et al., 2015). Therefore, while the extent of overestimation may be similar in absolute terms, between these features, it is likely to produce the greatest impact for colour, where it would be – relatively - the largest. Furthermore, by using a fixed duration, rather than one tailored to each observer, they overlooked the considerable degree of individual variability in the duration required for consolidation (range 47–117 ms, Experiment 1 of Miller et al., 2014).

In summary, recent developments indicate a striking inconsistency regarding the underlying properties of VWM consolidation between those features that have been shown to be encoded in parallel: a reduction in precision associated with motion direction, but none for colour. Resolving this discrepancy is critical for developing a theoretical understanding of VWM consolidation. Here we address two possible explanations by investigating parallel consolidation of colour while a) increasing the number of items presented, and b) tailoring the exposure duration of items.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Sixteen observers participated in Experiment 1. This sample size was selected in order to allow appropriate comparison with previous studies of parallel consolidation (Mance, Becker, & Liu, 2012; Miller, Becker, & Liu, 2014; Rideaux & Edwards, 2016). All observers had normal or corrected to normal visual acuity, gave informed written consent to participate in the study, were naïve regarding the aims of the experiment, and were compensated with either research credit or $15 for participation. All work was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.1.2. Apparatus

All experiments were run under the MATLAB (version R2013a) programming environment, using software from the PsychToolbox (Brainard, 1997; Pelli, 1997). In Experiment 1, stimuli were presented on a Phillips Brilliance 202P4 CRT monitor that was driven by an NVIDIA graphics card in a host Dell computer. The monitor had a spatial resolution of 1024 × 768 pixels and a frame rate of 120 Hz.

2.1.3. Stimuli and procedure

The stimuli and procedure were similar to that used by Miller et al. (2014). A 2 × 2 experimental design was employed: presentation (sequential/simultaneous) × set size (2/3). The stimulus presentation consisted of displaying target items, followed by backwards masking. In the simultaneous conditions, all items were presented at the same time then masked, whereas in the sequential condition, items/masks were presented serially and separated by a 500 ms fixation period after each mask. The items consisted of coloured squares (3° × 3° visual angle) which were presented on the corners of an imaginary square (11° × 11°) centred on fixation. The location (which corner) the items were presented was selected randomly (without replacement) on each trial. The colour of items was drawn at random from a colour wheel produced by sinusoidal modulation of RGB inputs (offset by 120° phase shifts), with the restriction that no two on the same trial could be within 15°. Items were presented for a predetermined duration, the determination of which is later described, followed by a 250 ms mask. The masks were the same size as the items, and presented in the same location/s; consisting of 10 × 10 smaller squares of colours selected randomly on each trial. Following presentation of items/masks, the colour wheel was displayed (14° radius) in addition to a light grey square in the (target) location of one of the previously presented items. The background was grey (mean luminance, 12 cd/m^2).

The observer's task was to use the mouse to indicate the colour of the item presented at the target location. Once the mouse was moved from fixation, the grey square became coloured with that corresponding to the location of the mouse. A schematic of the presentation sequence is show in Fig. 1.

The exposure duration of the items, determined before the main experiment, was tailored for each participant. The stimulus and procedure used were similar to that employed in the main experiment; however, here only a single item was presented. As in the main experiment, on each trial the item was randomly positioned in one of four possible locations. An adaptive staircase procedure was employed, using software from the Palamedes Toolbox (Prins & Kingdom, 2009), to determine the exposure duration at which observers could perform the task at threshold (75%) performance. The staircase began at 120 ms, was fixed at 50 trials, and was repeated if there was excessive variability in the last ten trials, i.e., standard deviation above 2 ms. Determining the shortest duration in which observers' could consolidate an item was critical to the experiment. If the criteria for a correct response in the thresholding procedure was too conservative, the threshold duration may be overestimated and observers could potentially serially consolidate two items at a lower resolution in the simulation presentation condition of the main experiment. Thus, responses were considered correct if they were within 30° of the target, approximately twice the standard deviation of responses in a previous parallel consolidation task (Miller et al., 2014).

In the main experiment, observers ran two blocks of each condition, randomly interleaved within a mega block. Each block consisted of 150 trials, totalling 1200 trials and an approximate testing duration of 1.5 h per observer.

2.1.4. Data analysis

For each trial, we calculated the offset (error) by subtracting the position of the colour recorded from the observer's response from that of the cued item. There are two main sources of variability within the offsets, resulting from two types of trials. One where the observer successfully consolidates the cued item into VWM, resulting in a von Mises distribution of offsets with a mean (μ) and standard deviation (σ)