Cerebral Cortex, 2023, 1–11
https://doi.org/10.1093/cercor/bhad378
Original Article

Dissociable online integration processes in visual working memory

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Visual working memory has severe capacity limits, creating a bottleneck for active processing. A key way of mitigating this limitation is by chunking, i.e. compressing several pieces of information into one visual working memory representation. However, despite decades of research, chunking efficiency remains debated because of mixed evidence. We propose that there are actually 2 integration mechanisms: *Grouping* combines several objects to one representation, and *object-unification* merges the parts of a single object. Critically, we argue that the fundamental distinction between the 2 processes is their differential use of the pointer system, the indexing process connecting visual working memory representations with perception. In grouping, the objects that are represented together still maintain independent pointers, making integration costly but highly flexible. Conversely, object-unification fuses the pointers as well as the representations, with the single pointer producing highly efficient integration but blocking direct access to individual parts. We manipulated integration cues via task-irrelevant movement, and monitored visual working memory's online electrophysiological marker. Uniquely colored objects were flexibly grouped and ungrouped via independent pointers (experiment 1). If objects turned uniformly black, object-integration could not be undone (experiment 2), requiring visual working memory to reset before re-individuation. This demonstrates 2 integration levels (representational-merging versus pointer-compression) and establishes the dissociation between visual working memory representations and their underlying pointers.

Key words: chunking; contralateral delay activity; EEG; pointer system; working memory.

Introduction

Visual working memory (VWM) holds representations in an active state, ready to be accessed and manipulated (Baddeley and Hitch 1974). One of the key characteristics of this mental workspace is its extremely limited capacity: People can hold only about 3 simple items' worth of information in this online state (Cowan 2001; for a recent analysis, see Balaban et al. 2019b). VWM's capacity creates a bottleneck for active processing, and therefore, numerous studies have attempted to investigate potential ways of mitigating this limitation. One of the most important and heavily studied of these processes is integration, i.e. chunking distinct features or objects into a single representation in VWM (e.g. Luck and Vogel 1997; Hollingworth 2007; Chen and Wyble 2015; Nassar et al. 2018; Balaban et al. 2019b).

Despite decades of research, the efficiency of VWM integration is still hotly debated. On the one hand, many studies have found that chunking leads to both behavioral benefits and reduced use of neural resources (Vogel et al. 2001; Woodman et al. 2003; Delvenne and Bruyer 2006; Peterson et al. 2015). On the other hand, there are studies that reported chunking to be costly or imperfect (Olson and Jiang 2002; Wheeler and Treisman 2002; Delvenne and Bruyer 2004). Importantly, currently no overarching theoretical model can explain the full set of evidence. Here, we argue that there are actually 2 distinct integration mechanisms, differing in their use of VWM's indexing system, which we describe next.

To maintain its active status, VWM must constantly modify its representations to reflect changes in the represented items, for example, as they move or interact (Blaser et al. 2000; Drew and Vogel 2008; Ankaoua and Luria 2022). This ability depends on maintaining a continuous correspondence between each VWM representation and an actual item in the world, i.e. a pointer system (Pylyshyn 2000, 2001; see also Kahneman et al. 1992; Levillain and Flombaum 2012), allowing VWM to access the correct representation and modify only it. Recently, we found that if this correspondence is invalidated, VWM has to reset, by discarding the original, unmapped representations, and replacing them with new ones (Balaban and Luria 2017; Balaban et al. 2018a, 2018b, 2019a). This happens, for example, when a coherent object splits in 2, because of the misalignment between the 2 now-independent units and the original single representation. Resetting is accompanied by pronounced and specific neural and behavioral signatures, which can be used as evidence that some event invalidated the perception-to-VWM mapping.

We propose 2 dissociable integration mechanisms that can compress information into a single VWM-unit, yet involving different pointer system mappings (Fig. 1). Grouping combines *different objects*, whereas object-unification merges the *different parts or features of one object*. This distinction allows reinterpreting past results as showing that object-unification through physical fusion (e.g. a bar's color and orientation; Luck and Vogel 1997) is highly efficient, whereas grouping by Gestalt cues (e.g. Kanizsa shapes;

Received: June 6, 2023. **Revised:** September 16, 2023. **Accepted:** September 17, 2023
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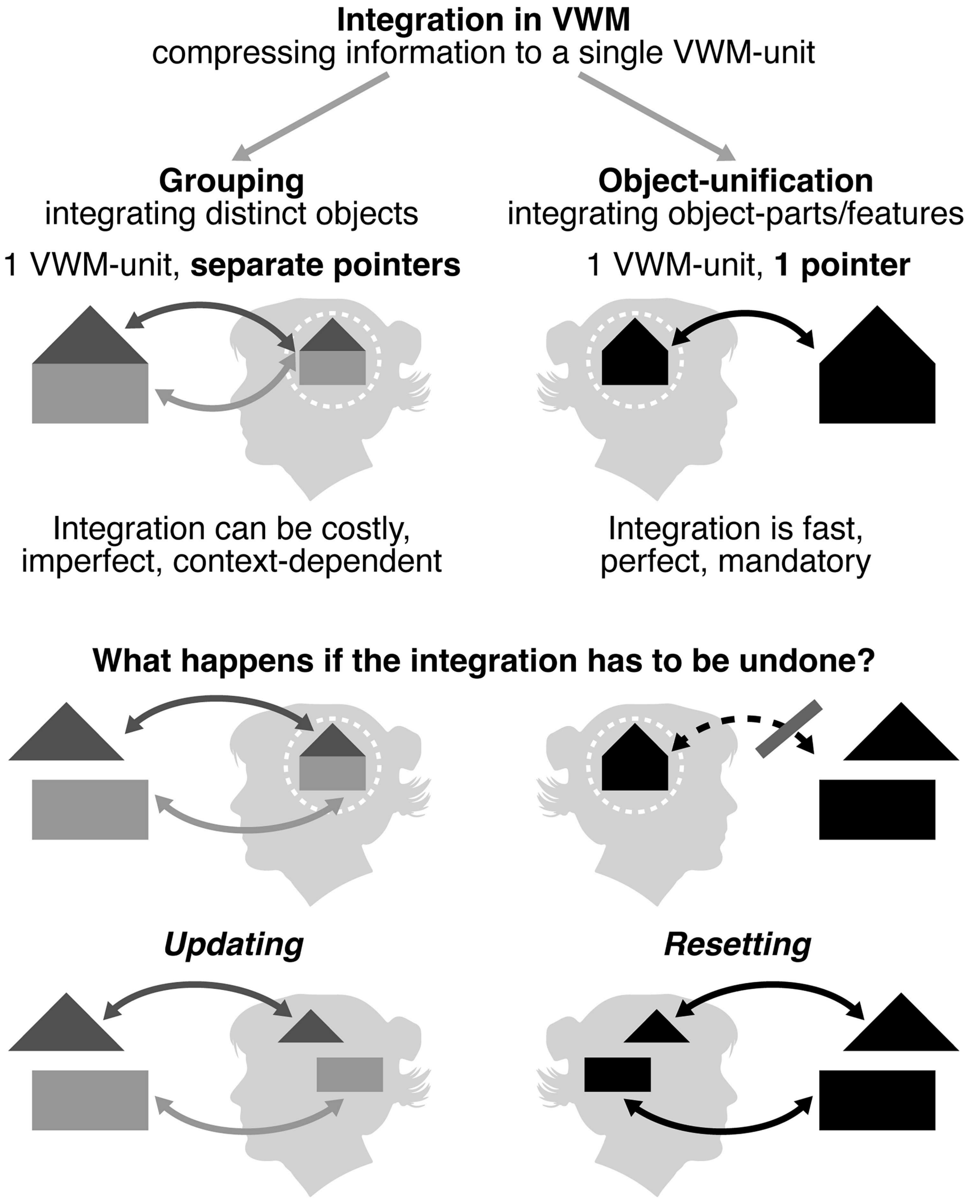

Fig. 1. The proposed distinction between grouping (left) and object-unification (right), two integration mechanisms that rely on different perception-to-VWM mappings, independent versus merged, respectively.

Gao et al. 2016) is costly and sometimes imperfect (see the Discussion). Critically, we suggest that in object-unification *not only the representations but also their pointers are merged*, whereas in grouping, *each object maintains an independent pointer*.

Notably, we follow the “fingers of instantiation” literature (Pylyshyn 2000, 2001) in viewing pointers as indexes of individuation that do not carry the representational content itself (an item’s features), but mark an item as a coherent unit to be tracked even if its features (including, but not being limited to, its location) change. Therefore, the number of active pointers does not necessarily align with the number of active VWM-units (or slots), and we make specific predictions about situations that dissociate them. Other recent investigations of pointers (e.g. Thyer et al. 2022) rely on a similar distinction between representational content and individuation indexes, but dissociate from the present claims in two important ways. First, they argue that pointers rely on spatiotemporal information, whereas we have previously shown that pointers are assigned to objects, even when objects are contrasted with featural and spatial information (Balaban et al. 2019a). Second, they interpret pointers as roughly equal to what has been previously referred to as slots, whereas here we go further than that, in suggesting and empirically supporting the claim that several pointers can occupy a single slot.

A novel prediction of the distinction we propose between the two integration mechanisms revolves around accessing a specific part of the integrated representation. This should be easy in grouping, because each object retains its independent pointer. In contrast, in object-unification, the access to each part is lost when the pointers are merged, and hence VWM should reset before the parts can be represented as separate items again.

Our main measure of online processing is the contralateral delay activity (CDA; Vogel and Machizawa 2004; Luria et al. 2016; Adam et al. 2018), an event-related potential (ERP) index of VWM whose amplitude rises with the number of VWM-units. The CDA

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also faithfully reflects the dynamics of the pointer system (Balaban and Luria 2019), transiently dropping following resetting if the VWM-to-perception mapping is disrupted (Balaban and Luria 2017; Balaban et al. 2018a, 2019a). This reliable and replicable effect is specific to pointer-invalidation events, whereas extremely similar situations that allow the mapping to hold translate to a stable CDA change, without a drop, reflecting an updating process (e.g. Drew et al. 2012; Luria and Vogel 2014; Balaban and Luria 2015). Thus, the CDA can be examined in 2 ways: The "stable" amplitude indicates the number of active representations, and the presence versus absence of a drop after a certain event indicates whether the event caused VWM to reset or allowed it to continue updating.

We conducted 2 EEG experiments with extremely similar stimuli that only minimally differed to invoke different integration mechanisms. In a shape-VWM task, we manipulated integration cues via task-irrelevant movement, having shape-halves move separately, meet and move together, and then re-separate. In experiment 1 (grouping), each shape-half had a unique color, supporting separate pointers throughout. In experiment 2 (object-unification), the halves turned black after meeting, creating a uniform compound shape that supports only one pointer. We hypothesized that for both grouping and object-unification the joint movement would reduce the number of representations held in VWM, manifesting in a reduced CDA amplitude. The important difference between the two experiments, following the proposed distinction between the two integration mechanisms, should occur after items re-separate. Specifically, in experiment 1, items should be easily ungrouped via an updating process, translating to a steady change in CDA amplitude, whereas in experiment 2, a resetting process is required before object-unification is undone, which should trigger a CDA-drop.

The contributions of this paper are three-fold. First, we propose a currently missing overarching theoretical framework for VWM-integration. Second, we provide novel empirical support for this framework. Third, we connect the rich literature of VWM-integration with the newer research tradition of the pointer system.

Materials and methods

Participants

Participants were Tel Aviv university students, with normal or corrected-to-normal visual acuity and color-vision, who gave informed consent following the procedures of a protocol approved by the local ethics committee. Each experiment included 16 naïve participants (experiment 1: 12 females, mean age 23; experiment 2: 9 females, mean age 23.3). Participants with a >25% rejection rate because of blinks or eye movements were replaced: 1 in experiment 1 and none in experiment 2. Sample size was determined based on a $d = 1.07$ effect size from a similar experiment (Balaban and Luria 2017), which required 8 participants for 80% power; we doubled this sample size to ensure a high probability of revealing any effects of interest. Our focus in this paper was the within-subjects effects of each experiment, and this is what the a priori power calculation was based on, but because one important claim relies on a null result in experiment 1 (see below), after collecting the data we decided to also conduct a between-subjects comparison, to make sure the 2 experiments significantly differ. The fact that the present study is not sufficiently powered for a between-subjects comparison is a shortcoming, and future studies along the same lines should verify this result in a larger sample or a within-subject design mixing the 2 conditions.

Stimuli and procedure

We used a lateralized version of the change detection task, allowing us to isolate any VWM processes while controlling for low-level processes. Each trial started with a 750 ms fixation display of a black cross (0.4° × 0.4°; viewing distance ~60 cm) in the center of a gray screen. Then, two white arrows (1.9° × 0.4°) appeared for 200 ms, pointing either left or right (randomly determined with an equal probability), indicating the to-be-attended side for the upcoming trial. After a 300 to 500 ms (randomly jittered) fixation, the memory array appeared, with 4 shape-halves in each side (from here on, when describing the number of items, we always refer only to the relevant side). There were 4 top-half and 4 bottom-half shapes (1.6° × 0.8°), which could form 16 different compound shapes, and each appeared in 1 of 6 highly distinct colors: yellow, green, blue, purple, red, and brown. Items' shape and color were chosen randomly without replacement (independently for each side) on each trial, such that there were 2 top- and 2 bottom-half shapes. Items appeared at random locations at least 1.6° apart, inside an invisible 8.5° × 3.7° area. The items moved in straight lines for 2000 ms, remained stationary for another 300 ms, and disappeared for 900 ms. The items then reappeared, and participants indicated, in an unspeeded manner, via button press (using the "z" and "/" keys) whether one shape-half changed its shape (50% probability; a top-half changed to a new top-half, or a bottom-half to a new bottom-half). In all, 12 practice trials were followed by 14 experimental blocks with 60 trials each.

The 4 conditions differed only in the movement sequence, which was completely task-irrelevant, as the change detection task only required participants to indicate a change in one of the shape-halves. In the baseline *Separate halves* condition, each shape-half moved independently. In the baseline *Integrated* condition, the 4 shape-halves formed 2 compound shapes, made of a top-bottom pair that moved as a coherent unit throughout the movement phase. The *Separating* condition started like the Integrated condition, but after 1600 ms the compound shapes split into halves that moved away from each other. The *Joining-separating* condition was identical to the Separating condition, except for the initial 600 ms of movement, which was separate (i.e. the halves moved toward each other for 600 ms, met and moved together for 1000 ms, and re-separated for the remaining 400 ms). To ensure participants' attention to the initial movement, 10% of the trials (25% in the first block) were catch trials, in which the memory array ended after the initial 300 ms. These trials were not further analyzed.

Experiments 1 and 2 were identical except for items' (task-irrelevant) colors, which remained unique in experiment 1, and turned all black after 600 ms (coinciding with the meeting in the Joining-separating condition) in experiment 2.

EEG recording and analysis

EEG was recorded inside a shielded Faraday cage, using a BioSemi ActiveTwo system, from 32 scalp electrodes at a subset of the extended 10-20 system, and from 2 electrodes placed on the mastoids. EOG was recorded from 2 electrodes placed near the external canthi, and from an electrode beneath the left eye. Data were digitized at 256 Hz. Offline signal processing was performed using EEGLAB Toolbox (Delorme and Makeig 2004), ERPLAB Toolbox (Lopez and Luck 2014), and custom MATLAB (The MathWorks, Inc.) scripts. All electrodes were referenced to mastoids average.

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Continuous data was epoched from −200 to +3200 ms from memory onset (i.e. end of the retention interval).

Artifact detection used a sliding window peak-to-peak analysis, with a threshold of 80 μV for EOG, and 100 μV for the analyzed electrodes (see below), resulting in a mean rejection rate of 10% in experiment 1, and 9.4% in experiment 2 (for evidence that eye movements are not responsible for the CDA-drop, see Balaban and Luria 2017; Balaban et al. 2018a, 2019a). We further conducted an analysis targeting eye movements, calculating the average horizontal EOG for the left and right cued trials in the analyzed time windows (Woodman and Luck 2003). We found that on average, eye movements were small, with a mean HEOG of 2.2 μV in experiment 1 and 2.5 μV in experiment 2, both translating to $<0.2^\circ$ of visual angle (Hillyard and Galambos 1970). We identified 3 participants (2 in experiment 1 and 1 in experiment 2) with an average HEOG difference between left and right cued trials exceeding 5 μV (Wang et al. 2019). Removing these participants from the CDA analyses did not change any of the results, providing further support to the finding that the CDA and the resetting drop do not reflect eye movements, and are not largely affected by them. Because including the participants with larger eye movements did not change the present conclusions, we report the results including all 16 participants in each group.

For plotting purposes, the epoched data were low-pass filtered using a noncausal Butterworth filter (12 dB/oct) with a half-amplitude cutoff point at 30 Hz. Statistical analyses were performed on the unfiltered data, to avoid potential effects of filtering on the observed results (Woodman 2010). Only trials with a correct response were included in the analysis.

Epoched data were averaged separately for each condition, and the CDA difference wave was calculated by subtracting ipsilateral from contralateral activity (relative to the memorized side). This subtraction ensures the CDA exclusively reflects VWM processes, and is immune to related processes such as perception, spatial attention, or eye-movement, as has been extensively shown in the past (e.g. Ikkai et al. 2010; Luria et al. 2010; Kang and Woodman 2014; Feldmann-Wüstefeld et al. 2018). As was done in previous studies (Balaban and Luria 2017; Balaban et al. 2018a, 2019a), we report the results from the average of 3 electrode pairs (P7/8, PO3/4, and PO7/8), but we found the same patterns of activity in each pair separately (for an analysis of the spatial distribution of the CDA-drop, see Balaban and Luria 2019).

To determine whether the items were integrated in VWM, we analyzed CDA mean amplitude in 2 parts of the memory array (for a similar approach, see Drew et al. 2011, 2012, 2013; Luria and Vogel 2014; Peterson et al. 2015; Balaban and Luria 2016a), 600 to 1200 ms and 1200 to 1800 ms from trial onset ("early" and "late" windows, respectively), i.e. before the separation could affect the CDA (which takes about 200 ms to respond; Vogel et al. 2005). Because of their previous separate movement, we expected items of the Joining-separating condition in both experiments to be held separately in VWM in the early window, and to become integrated in the late window (see, e.g. Luria and Vogel 2014; Balaban and Luria 2015). A resetting process is observed in the CDA ~200 ms after pointer-invalidation events (here, items' separation), while if the VWM-to-perception mapping holds there is no drop, even for very similar situations. As was done in previous work, we defined the "resetting" time window as 200 to 300 ms after separation (Balaban and Luria 2017; Balaban et al. 2018a, 2019a), and compared it with the "pre-resetting" window immediately preceding it (100 to 200 ms after separation, i.e. comparing the time windows 1700 to 1800 ms and 1800 to 1900 ms from trial onset; Balaban and Luria 2017). We use this approach instead of comparing the resetting window between different conditions to avoid the potential effects of the recently reported "resetting mode" (Friedman and Luria 2022), whereby the resetting effect might leak into the control conditions. For statistical tests, we performed analyses of variance, followed by planned comparisons (contrasts), the results of which are reported, for simplicity.

Results

Experiment 1: grouping

All conditions of our shape change detection task included 4 shape-halves, differing only in their movement sequence (see Fig. 2A). We monitored the CDA (Vogel and Machizawa 2004; Luria et al. 2016; Adam et al. 2018), an ERP index of VWM that can reveal different aspects of online processing. First, the CDA's amplitude is higher when more VWM-units are held, meaning that any type of integration leads to a lower amplitude as the information is compressed into a smaller number of active representations (e.g. Luria and Vogel 2011; Peterson et al. 2015). The CDA also reflects the dynamics of the pointer system. The presence of a drop in CDA amplitude ~200 ms after a certain event reveals a resetting process (Balaban and Luria 2017; Balaban et al. 2018a, 2019a; Park et al. 2020; Friedman and Luria 2022). Conversely, if the number of represented units increases or decreases without invalidating the pointer system mapping, the CDA amplitude would steadily change across time to indicate an updating process (e.g. Drew et al. 2012; Luria and Vogel 2014; Balaban and Luria 2015, 2016a, 2016b). These different ways of examining the CDA have been replicated and validated in many studies (for reviews, see Luria et al. 2016; Balaban and Luria 2019). Here, the 2 baseline conditions included fully independent (the Separate condition) or fully joint (Integrated condition) movement. The Separating condition moved from separate to joint, and the Joining-separating condition started separately, joined, and then re-separated. Each shape half had a unique distinct color throughout the trial, which enables establishing distinct pointers for each half even when items move together (Balaban et al. 2018a). Therefore, we predicted a lower CDA amplitude during items' joint movement, indicating integration, but because of the independent pointers held in grouping, we predicted that the separation of the compound shapes is followed by an updating process, with a steadily rising CDA amplitude (i.e. no drop). The results of experiment 1, as can be seen in Fig. 2B, confirmed this prediction.

We first verified that integration indeed occurred following the joint movement. In both the early and late parts of the items' movement, both the Integrated and the Separating conditions had a lower CDA amplitude than the Separate halves condition (all $Fs > 10$, all $Ps < 0.007$, all Cohen's $ds > 0.7$), despite all conditions including the same 4 shape-halves. This shows that the common fate Gestalt cue caused items to be compressed in VWM, consuming less capacity, as has been previously shown (Luria and Vogel 2014; Balaban and Luria 2016a, 2016b). The Integrated and Separating conditions did not significantly differ during these times (both $Fs < 1.7$, both $Ps > 0.2$, both $ds < 0.4$), which is expected given that they were identical until a late stage of the movement.

Our focus was on items' separation: If each half can still be accessed using its independent pointer, VWM should be able to update post-separation, and individuated the representations without a CDA-drop in the previously defined resetting time window (Balaban and Luria 2017; Balaban et al. 2018a, 2019a). Indeed, the CDA in the Separating condition did not significantly differ between the pre-resetting and resetting time windows ($F < 1$), suggesting the representations easily became unintegrated after

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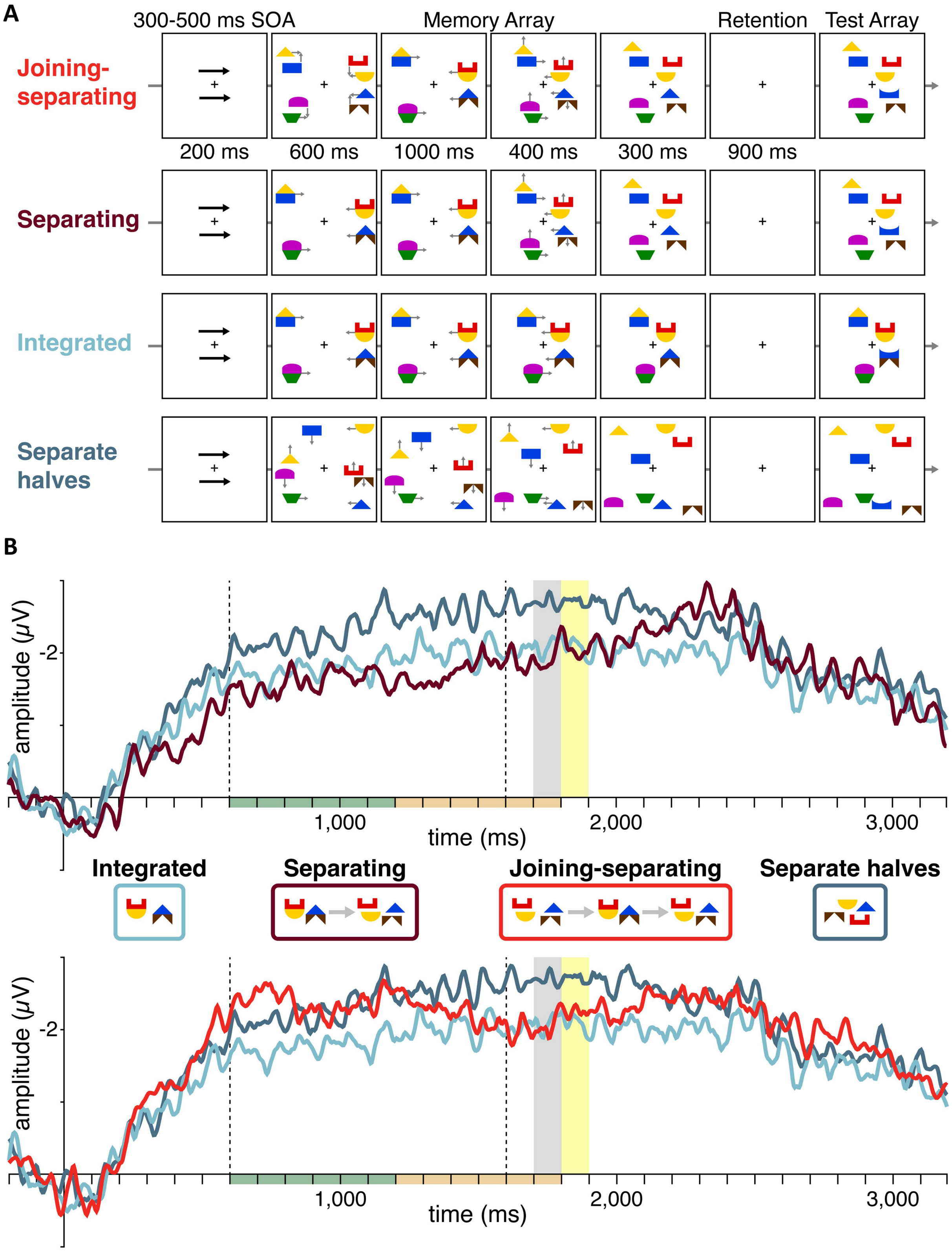

Fig. 2. A) The trial sequence in the different conditions of experiment 1. Participants monitored moving shapes for a change-detection task. Each shape-half had a unique color throughout the trial. Black arrows indicated the relevant side for the upcoming trial. Movement direction indicated by gray arrows that were not visible. Only a single shape-half could change, regardless of the condition. Color and movement were task-irrelevant. B) Experiment 1's CDA results (negative is up). The baseline conditions (separate halves and integrated) are presented in both panels, for easier comparisons with the separating (top panel) and joining-separating (bottom) conditions. Dashed lines show when items met in the joining-separating condition (left bar in each panel) and separated in separating and joining-separating conditions (right bars). Colored rectangles depict analyzed time windows (from early to late): early presentation (green), late presentation (orange), pre-resetting (gray), and resetting (yellow), where there was no significant CDA-drop in any condition.

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separation. We argue that this is because during the joint movement, the halves in each compound shape were held in the same VWM-unit (as shown by the low CDA amplitude), but each half still maintained its own independent pointer. Despite the representations being integrated (grouped) when moving together, the separate pointers allowed VWM to easily access each half and separate their representations when the integration cues changed.

To verify the independent status of the pointers in grouping, we examined the Joining-separating condition. In the early part of the items' presentation, immediately after the shape-halves met, the Joining-separating condition was still not integrated, producing a CDA amplitude higher than the Integrated condition ($F(1, 15) = 47.43$, $P < 0.001$, $d = 1.72$) and not significantly different from the Separate halves condition ($F(1, 15) = 1.60$, $P = 0.225$, $d = 0.32$). This shows that the halves' initial separate movement led each of them to be represented separately in VWM, presumably with independent pointers. After a period of joint movement, in the later part of their presentation, the Joining-separating condition was successfully integrated, producing a CDA amplitude lower than the Separate halves condition ($F(1, 15) = 5.45$, $P = 0.034$, $d = 0.58$), and not significantly different from the Integrated condition ($F(1, 15) = 1.31$, $P = 0.270$, $d = 0.29$). Importantly, we claim that even though the representations were now successfully integrated, i.e. compressed into one VWM-unit, the pointers still held their independent status. This was supported by the lack of a CDA-drop, such that the amplitude during the resetting time window was not significantly different from the pre-resetting time window ($F(1, 15) = 1.48$, $P = 0.243$, $d = 0.30$). This suggests that in the Joining-separating condition, as well as in the Separating condition, despite the integration of the representations (as shown by the low amplitude before the separation), the pointers were still independently accessible because of the distinct colors, allowing VWM to update following the separation without the need to reset. Thus, the results demonstrate that in grouping, distinct objects are combined into a single VWM representation while still maintaining separate pointers.

Experiment 2: object-unification

In experiment 2, the items' unique colors turned black during their movement (after 600 ms, corresponding to when halves met in the Joining-separating condition), in all conditions (see Fig. 3A). This caused the 2 halves in each compound shape to be perceived as a single object, which should prevent maintaining the independent pointers initially associated with each object. Instead, each compound shape should now support a single pointer, as we claim occurs in object-unification. Therefore, during the joint movement, we expected a lower CDA amplitude, similarly to experiment 1, but here this integration relies on a single pointer, so when a compound shape separates, we predicted a resetting process and a CDA-drop. The results of experiment 2 confirmed this prediction, as can be seen in Fig. 3B.

Items were again successfully integrated in VWM, resulting in lower CDA amplitudes in the Integrated and Separating conditions than the Separate halves condition, already during items' early presentation (both Fs > 5, both Ps < 0.04, both ds > 0.5). The integration of the Joining-separating condition took longer to complete, because of the initial independent movement phase. The shape-halves in this condition were initially represented separately in VWM, with a CDA amplitude not significantly different from the Separate halves condition in the early time window ($F < 1$), but eventually became integrated, with a late CDA amplitude not significantly different from the Integrated condition ($F(1, 15) = 1.80$, $P = 0.199$, $d = 0.34$). Thus, the joint movement was successful in integrating the representations in VWM. Notably, if simply any change in pointer distribution causes a resetting process, we would expect to find a CDA-drop also 200 ms after the items meet and turn black, because the pointer system presumably moves from holding two pointers to a single one. Instead, the resetting process is specific to events that create a correspondence problem, and in pointer-merging there is no such problem (one can think of the asymmetry between adding 1 and 1, which gives another integer, and dividing 1 by 2, which is no longer an integer), which is why the CDA did not drop after joining but only after separation.

Critically, we claim that once the shape-halves moved as a uniform object (all black), VWM would integrate not only their representation but also their pointers. The lack of access to the original independent pointers in object-unification necessitates a resetting process before separate representations can again form (Balaban and Luria 2017; Balaban et al. 2018a, 2019a). Indeed, we found that for both the Separating and Joining-separating conditions, the amplitude in the resetting time window significantly dropped compared with the pre-resetting window (both Fs > 6, both Ps < 0.03, both ds > 0.6). Notably, the CDA in the present experiment does not drop all the way to baseline, a result that has been replicated many times for relatively familiar shapes (e.g. Balaban et al. 2019a). This could be either because there is a larger percentage of trials or participants for which there is no drop at all (while for others, the CDA drops all the way to 0), or because the re-encoding or re-individuation stages of the post-separation representations is easier (Balaban and Luria 2019; these ideas are not mutually exclusive). The lower CDA amplitude indicates a loss of information from VWM, in line with the hypothesis that the separation caused a correspondence problem, meaning the pre-separation representations of the integrated compound shapes had to be removed from VWM and replaced by new independent representations of each shape-half. This suggests that in object-unification, unlike in grouping, integration involves not only the representations but the pointers.

Comparing grouping and object-unification

To establish the difference between our two experiments, we compared the resetting effect between them, and found a significant interaction ($F(3, 30) = 3.16$, $P = 0.029$, $\eta^2 = 0.07$), driven by a larger resetting effect in the Separation and Joining-separating conditions of experiment 2 (both Fs > 5, both Ps < 0.04, both ds > 0.8). This corroborates our claim that to undo object-unification VWM must reset, whereas grouping can be undone without a resetting process.

For completeness, we also analyzed participants' accuracy. However, accuracy in our task cannot reveal the ongoing dynamics of integration, because it is measured after the items stop and disappear for the retention interval, i.e. long after the online movement cues (for a behavioral investigation of online pointer-system processes using a different task, see Balaban and Luria 2017; Balaban et al. 2018a, 2018b). We predicted a behavioral benefit for both types of integration, but did not expect to find a difference between them. This is because any stronger integration-benefit for object-unification over grouping could be balanced by an opposite task-benefit for the uniquely colored stimuli in the grouping experiment, given that the task is performed on individual halves and these stimuli are easier to individuate and compare during the test. Both types of integration produced a behavioral benefit, with higher accuracy in the Integrated condition (mean = 0.76 in both experiments) than in all of the

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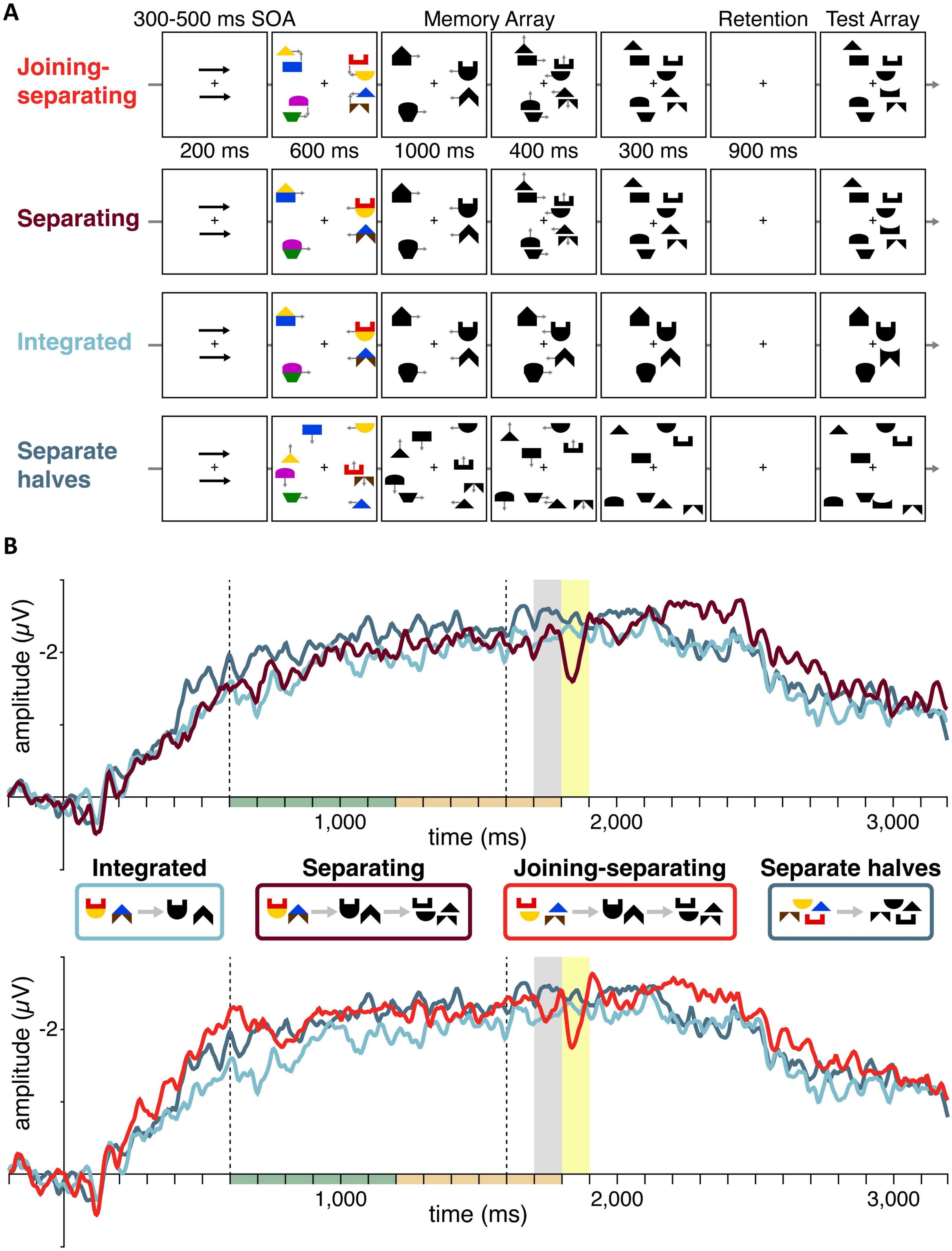

Fig. 3. A) The trial sequence in the different conditions of experiment 2. Participants monitored moving shapes for a change-detection task. Each shape-half started in a unique color, and all turned black after 600 ms. Black arrows indicated the relevant side for the upcoming trial. Movement direction indicated by gray arrows that were not visible. Only a single shape-half could change, regardless of the condition. Color and movement were task-irrelevant. B) Experiment 2's CDA results (negative is up). The baseline conditions (separate halves and integrated) are presented in both panels, for easier comparisons with the separating (top panel) and joining-separating (bottom) conditions. Dashed lines show when items met in the joining-separating condition (left bar in each panel) and separated in separating and joining-separating conditions (right bars). Colored rectangles depict analyzed time windows (from early to late): early presentation (green), late presentation (orange), pre-resetting (gray), and resetting (yellow), where there was a significant CDA-drop in the separating and joining-separating conditions.

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other conditions (means raging between 0.69 and 0.73; all $Fs > 8$, all $Ps < 0.015$, all $ds > 0.7$), despite all conditions including the same 4 shape-halves, with the task involving detecting a change in a single half. The two experiments did not differ in their behavioral effects ($F < 1$), most likely because of the task used, which tested each shape-half separately, and therefore privileged the uniquely colored stimuli of experiment 1. Importantly, many past studies have already established the presence of incomplete behavioral benefits with grouping in different contexts (e.g. Wheeler and Treisman 2002; see also the Discussion).

Discussion

The goal of this study was to offer a theoretical distinction between 2 types of VWM integration (grouping and object-unification), relying on different mechanisms, and to provide empirical support for this claim from two EEG experiments.

At the conceptual level, we suggest that the two integration processes operate on different levels: Object-unification combines several object-parts into a single coherent object, and grouping compresses several distinct objects into one ensemble. To illustrate, grouping helps processing the trajectory of many people that cross a street together, because of their uniform motion, whereas object-unification enables tracking the trajectory of one car as a single whole, without separately computing how each of its part moves. At the mechanistic level, despite the fact that both processes involve holding more information in a single VWM-unit, we argue that grouping and object-unification fundamentally differ in the item-to-representation mapping they involve. In grouping, the representations are integrated, while still retaining their independent pointers. This allows VWM to access each object separately and, when appropriate, update the representation to become separate. On the other hand, in object-unification, not only the representations but also the pointers are merged, such that the entire object supports only a single pointer, and consequentially there is no access to the parts in an independent manner. Therefore, if the parts are to be separately held in VWM, a resetting process is necessary, i.e. removing the existing whole-object representation, and encoding new representations of each separate part.

The two EEG experiments presented here harnessed the CDA to support this novel theoretical suggestion. Experiment 1 included easy-to-individuate (uniquely colored) objects forming groups, and indeed we found a steady change in CDA amplitude following separation, in line with an updating process that relied on the accessibility of independent pointers. Importantly, we would predict similar results with other manipulations that make the halves easy to individuate, and hence encourage holding on to independent pointers, such as keeping the halves slightly apart during their joint movement phase, using figure-ground stimuli, or even clearly defining separate objects by presenting familiar objects in spatial relationships (e.g. placing a mug on top of a table). Experiment 2 presented hard-to-individuate (uniformly colored) parts forming objects, and their separation triggered a resetting process, with a sharp drop in CDA amplitude before the parts could be individuated again. It is important to note that the fact we could find a CDA-drop even for the Joining-Separating condition of experiment 2 rules out an interpretation of this effect as reflecting some general surprise signal. The study did not include a condition where items just met and did not later separate, making the re-separation perfectly predictable. Still, the fact that the object split apart, despite being completely not surprising, breaks the correspondence between VWM and ongoing perception. This corroborates the interpretation of the CDA-drop as a specific index of pointer system disruption.

The distinction between compressing only the representations (in grouping) or also the pointers (in object-unification) can explain the seeming discrepancy in VWM integration studies. While some studies reported a complete integration, others found it to be imperfect or costly, resulting in researchers in the field holding contrasting views about the efficiency of integration. For example, color–color conjunction stimuli produce incomplete integration (Olson and Jiang 2002; Wheeler and Treisman 2002; Delvenne and Bruyer 2004; Luria and Vogel 2011, 2014; Parra et al. 2011; although see Luck and Vogel 1997; Vogel et al. 2001), leading many researchers to argue for limited integration in items with features from the same dimension. A similar pattern was also observed with two colors organized by uniform connectedness (Peterson et al. 2015) and two orientations forming a Kanizsa shape (Gao et al. 2016). However, our current findings suggest an alternative explanation, such that the critical factor is not whether features belong to the same dimension or to different ones, but whether they belong to the same object or to different ones. This would classify all of the weak-integration studies mentioned above (e.g. with Kanizsa shapes) as grouping, because the parts are easily individuated, meaning the reason for the incomplete integration could be the separate pointers each object maintains.

A prediction that arises from the present theoretical and empirical distinction is that regardless of the dimensions included, object-unification is more efficient than grouping. While few studies examined the integration of two different-dimension objects in a group (e.g. a tilted bar on top of a colored circle), those that did demonstrated behavioral and neural costs that were even more pronounced than for color–color conjunctions (Xu 2002a, 2002b; Delvenne and Bruyer 2006; Balaban and Luria 2016b). As a mirror image along similar lines, same-dimension object parts are perfectly integrated: Two shape-halves forming a whole shape produce the same CDA amplitude as a single shape-half (Balaban and Luria 2015). In short, we argue that past inconsistencies regarding the efficiency of VWM integration are because of the use of two types of integration, one of which (object-unification) is more complete than the other (grouping). This opens up fascinating questions for future studies, such as the time-course of each integration process, which can now be tackled in a clearer way, with respect to the distinction we suggest here between the two integration processes. Another interesting issue that can be targeted is how grouping and object-unification operate in complex real-world items, whose objecthood is supported not only by visual cues as used here, but also by semantic meaning.

The present results go further than dividing past mixed results in a theoretically coherent way, by suggesting and demonstrating distinct underlying mechanisms to explain the different behavioral and neural patterns. Namely, in grouping, the pointers remain separate, whereas in object-unification, they are merged. Merging pointers results in perfect integration, but comes with a potential cost, as was demonstrated here, because the integration cannot be undone without a resetting process. Previous studies have demonstrated that resetting even creates a behavioral cost: Changes in an object's parts are missed if they coincide with it splitting in two, in line with the claim that there is no access to the individual parts (Balaban and Luria 2017; Balaban et al. 2018a, 2018b). Importantly, in most everyday cases, resetting is not expected to be very common (e.g. coherent objects do not tend to split in two for no reason), and this process should be

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present only in situations such as when some kind of change leads us to drastically change our interpretation of objects or events, similar to the feeling arising during a magic show. This rarity of resetting means that object-unification remains highly efficient, but the existence of resetting does provide a very useful tool for establishing the limits of the pointer system.

In contrast to object-unification, grouping allows each item to retain some level of independence even after integration, via the separate pointers. This independency makes grouping not only less efficient, but also more flexible: Instead of being mandatory, this type of integration depends on factors like task demands or the context offered by the other conditions in the task (Balaban and Luria 2016a, 2016b). Considering this, it is interesting that grouping indeed happened in the Joining-separating condition of experiment 1, where re-separation was fully predictable. In the past, we found that a fully predictable joining-separating condition did allow participants to hold independent representations and avoid resetting, even when the two halves had the same color throughout (Balaban and Luria 2017), but this was true only for a very short joint movement phase. The present finding that a longer movement phase induced integration despite a fully predictable future separation, and specifically for items that are visually distinct, points to the extent to which our cognitive system relies on VWM integration, a process that in our everyday lives serves as an important tool alleviating the strict capacity limit of VWM (Cowan 2001). We see great value in the future pursuit of perusing questions such as how mandatory are different types of integration, and what kinds of cues are most important for the fate (integrated or separate) of representations. We believe that the present unified framework of VWM integration provides new hints to these lines of research.

An interesting question is whether and how binding—the integration of an object's different features (e.g. a bar's color and orientation)—maps onto our suggested distinction between grouping and object-unification. Binding has been heavily studied in the VWM literature, and most studies reported a highly efficient process, with robust (although not necessarily perfect) behavioral benefits and full CDA-reductions (e.g. Luck and Vogel 1997; Vogel et al. 2001; Luria and Vogel 2011), suggesting an object consumes similar VWM capacity regardless of the number of features it has. Binding thus seems very similar to object-unification, with all of an object's features being supported by a single pointer, which future research could directly test. In line with this, recent evidence shows that pointers are assigned to coherent objects, meaning that the pointer system is object-based (Balaban et al. 2019a), and not spatiotemporal as was previously suggested (e.g. Thyer et al. 2022).

Our results also provide strong evidence for a dissociation between VWM's representations and their supporting pointers. Specifically, in the Joining-separating conditions of both experiments, representations transformed from independent to integrated to independent (4 VWM-units to 2 and back to 4), but the pointers followed a different pattern in each experiment. Note that simply comparing the CDA amplitude of two conditions cannot reveal the hidden pointers, because several pointers can be associated with a single representation. This is the reason why grouping and object-unification led to similar reductions in CDA during items' joint movement. Exposing the differential pointer structure was made possible only by changing items' status (here, the integration cues) during the trial, and measuring a specific pointer system marker to test whether the mapping was invalidated by this change. In experiment 1, the updating process following separation indicated that the pointers remained independent even when the grouping integration took place, because of the unique colors. Contrarywise, in experiment 2, the resetting process, which was necessary before the representations could become separate again, suggests that the pointers themselves became merged when the compound shapes turned uniformly black. In line with previous theoretical conceptualizations (Pylyshyn 2000), pointers can be seen as indices of individuation that do not carry the actual representational content (e.g. object features). The present results show that the extra level of pointers, connecting the ongoing perceptual input and the dynamic VWM representations, is indeed necessary to explain the complete pattern of online dynamics.

Conclusion

In this paper, we suggested and experimentally demonstrated a new framework of integration in VWM (i.e., chunking items or features together), revolving around the pointer system – a set of unique mappings that connect perception and VWM representations. We put forward a distinction between two integration processes, namely grouping and object-unification. In grouping, unique objects are compressed into one VWM-unit, but maintain independent pointers, and hence integration can be easily undone via an updating process (experiment 1). In object-unification, the parts of a single object are merged, and their pointers are fused into one, meaning that now VWM is accessing the object as a single whole and a resetting process is required before the parts can be re-individuated (experiment 2). We argue this distinction between grouping and object-unification explains seemingly-inconsistent past results, as well as establishes the importance of the construct of pointer system mapping as distinct from the contents of VWM representations.

Author contributions

Halely Balaban (Conceptualization, Data curation, Formal analysis, Writing—original draft, Writing—review & editing), Trafton Drew (Conceptualization, Writing—review & editing), and Roy Luria (Conceptualization, Writing—review & editing)

Funding

A Binational Science Foundation (grant number 2015301 to RL and TD); an Israel Science Foundation (grant number 1589/23 to RL); an Azrieli Fellowship to HB, while at Tel Aviv University.

Conflict of interest statement: None declared.

Data availability

All data and code are available at https://osf.io/4w8jx.

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