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Visual working memory's pointer system: Past, present, and future

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ABSTRACT

In our everchanging environment, the online representations of visual working memory (VWM) have an extremely important role, as they can be modified to reflect changes in the items that are being represented, which requires some way of accessing the appropriate representation. This access is at the heart of VWM's pointer system, an indexing of specific representations via a one-to-one mapping between VWM and objects in the environment. Here, we first review classic findings leading to the development of this notion of VWM-pointers, with a special emphasis on the theoretical distinction between the indexes and the representational content. We then describe a recently established approach for studying VWM's pointer system, which focuses on directly manipulating the number of pointers and their validity. Specifically, when the mapping between an item and its corresponding VWM representation is invalidated (e.g., when an object is abruptly replaced by another one), the representation becomes inaccessible and cannot be updated. Instead, VWM resets by removing the unmapped representation, creating novel representations and allocating their pointers. Resetting has unique neural and behavioral signatures, which were successfully used for studying VWM's pointer system, by identifying the underlying requirements for its ongoing function. We present several important lines of research employing this approach and discuss key findings regarding diverse issues such as pointer assignment, VWM chunking, and intuitive physical expectations. We end by proposing promising directions for future work targeting VWM's pointer system, with the potential to uncover currently unknown aspects of this central cognitive mechanism.

1. Introduction

One of the greatest challenges our daily environment poses for the human mind is the hectic nature of its occupants. Because things around us constantly move and change, dramatically different percepts can originate from the same entity in the world. Yet, there are also transformations in internal factors, like movements of the eyes, head, or body; only some perceptual changes reflect true external changes, and the others should be somehow discounted. An important mechanism for dynamic-but-stable representations is visual working memory (VWM; Bays et al., 2024; Cowan, 2001; Luck and Vogel, 2013; Ma et al., 2014), an online workspace that holds a limited amount of information in an active state. Once something is represented in VWM, this representation can be modified to reflect a variety of possible changes to the represented real-world item (e.g., Blaser et al., 2000; Drew et al., 2011; Drew and Vogel, 2008; Peterson et al., 2015). VWM's ability to modify its representations leads to an important question: When a specific part of the environment changes (e.g., a particular object[1] changes its features), how can the relevant VWM representation be accessed so that it is appropriately modified?

Here, we argue and present evidence that this ability of VWM to access and update its representations in the face of an ever-changing world relies on a one-to-one mapping between each representation in VWM and a portion of the external environment (available via perception). This is necessary for the correct representation to be accessed and modified when a given item changes in the world (see Fig. 1). The

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[1] Here and throughout, when referring to the external world, we use 'object' in a way inspired by developmental psychology, as in a clearly defined state of physical matter.

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process implementing this correspondence function is VWM's **pointer system**[2]: a set of individuation indexes that do not directly represent the environment, but rather serve as a required bridge between things in the world, as mediated by the rich but fleeing perceptual input, and their usable representations in working memory. In what follows, we first outline some of the initial empirical findings suggesting the necessity of a mapping between VWM and the external environment (Section 2), then describe a novel approach for manipulating VWM's pointer system (Section 3), and then present the theoretical insights from applying this approach in recent studies (Section 4). We end with open questions and important directions for future research (Section 5).

2. Early evidence for a pointer system in VWM

The first line of evidence for an online indexing system for visual information processing comes from the multiple object tracking (MOT) task that was introduced by Pylyshyn (Pylyshyn, 2006, 2004; Pylyshyn and Storm, 1988; Scholl and Pylyshyn, 1999). The classic task involves presenting participants with several simple items, all with the same color and shape (for example, an array of black disks). A subset of the items is briefly highlighted as targets (e.g., by changing to a different color before changing back), and then all identical items start to move in independent random trajectories. After a few seconds, all items stop, and participants are asked to indicate which of them were the designated targets before the movement. Numerous studies have demonstrated that people perform very well in this task under typical viewing conditions, but only if tracking is limited to a handful of objects that are not moving too quickly or too closely to one another (e.g., Alvarez and Cavanagh, 2005; Alzahabi and Cain, 2021; Erlikhman et al., 2013; Fehd and Seiffert, 2008; Feria, 2013; Franconeri et al., 2010, 2008). Research using MOT is vast (for a recent review, see Holcombe, 2023), but for the present purposes it is only important to note that under some non-trivial task conditions, people track a subset of dynamic objects in the scene, which different studies have shown is achieved by actively holding the targets in VWM (e.g., Drew and Vogel, 2008). Because all items are identical except for their location, and because this location also constantly changes, MOT success suggests that the visual system must have some way of keeping track of items as individuals. The process of individuation-based indexing which MOT relies on, as opposed to some kind of featural selection, is what we – following Pylyshyn – conceptualize as pointers.[3]

The idea that tracking does not rely on items' features was strengthened by two additional sources of evidence. Within the MOT task, participants largely fail to notice featural changes to the items they are tracking (e.g., Bahrami, 2003), and even struggle reporting their identity when each item is associated with some unique identifier (e.g., Horowitz et al., 2007; Oksama and Hyönä, 2004; Pylyshyn, 2004). Somewhat analogously, developmental studies have demonstrated that pre-verbal infants' are sensitive to the number of objects they see before they are sensitive to the unique properties of these objects, and form expectations based on how many objects are in a scene without any expectations about these objects maintaining their shape or color (for example, Leslie et al., 1998; Xu and Carey, 1996). These converging

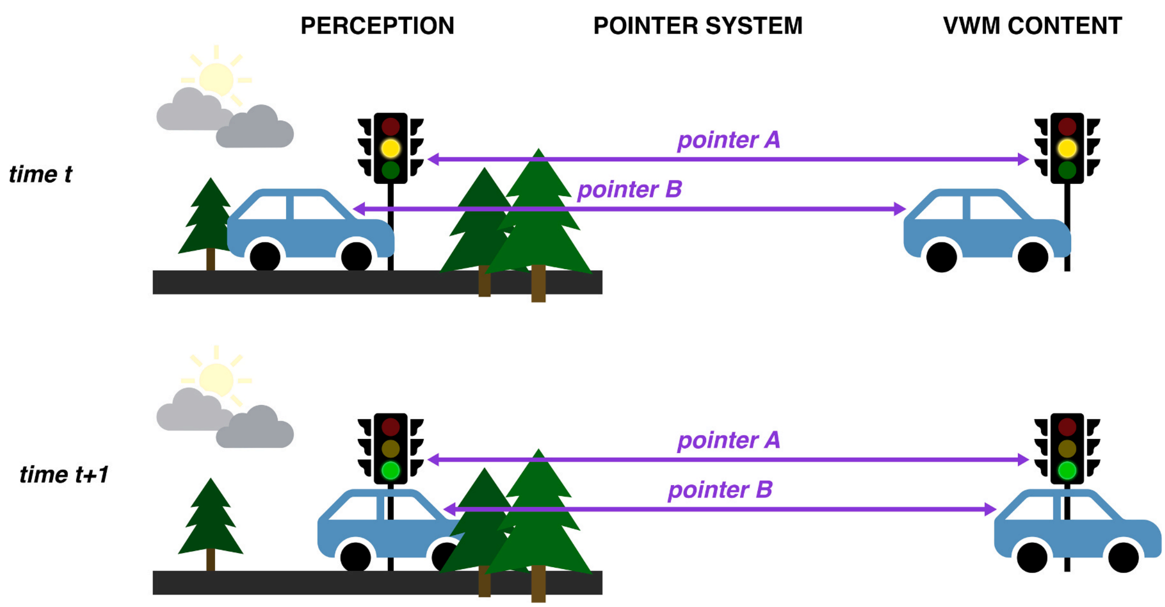

Fig. 1. A schematic sketch of a pointer system connecting perception and VWM. To handle changes in real-world items, each item that is encoded into VWM is mapped to a specific part of the external environment. This one-to-one mapping is carried out by a pointer system. Here, we present spatial and featural changes over time, but the same mechanism can also support other changes, like those brought about by the dynamics of eye-movements.

[2] Historically, several names have been used for similar ideas, most closely related to the current conceptualization is 'FINSTs', for fingers of instantiation, coined by Zenon Pylyshyn (e.g., Pylyshyn, 2001, 2000). We will use the term 'pointer system' to start from a theoretically-neutral position and only describe the key function.

[3] Aside from its non-featural nature, the mechanism underlying tracking was also claimed to work by parallel indexing of all the items, instead of rapidly switching between the different items within the indexed set. This was originally based on the fact that MOT performance was better than predicted by a serial spotlight model (Pylyshyn and Storm, 1988). The parallel indexing view later received further empirical support (e.g., Howe et al., 2010; Trick and Pylyshyn, 1994), but was also challenged by other data (e.g., Howard et al., 2011; Howard and Holcombe, 2008), and the issue is currently still debated in the literature (c.f. Holcombe, 2023). Here, we remain agnostic to the question of whether target *selection* happens in parallel or in serial, and we accept current evidence suggesting that *updating* representations (like modifying stored item locations in MOT) might happen serially (Balaban and Ullman, 2025a; Kessler and Meiran, 2008; Oberauer, 2002). Importantly, both these issues are theoretically distinct from the question of whether an individuation-based correspondence mechanism is indeed required for visual online processing.

evidence suggest that tracking is not based on the object satisfying some featural condition, meaning it only involves individuation, in line with the idea of pointers.

As another important source of motivation for a correspondence process, researchers usually turn to the object file literature (Kahneman et al., 1992). In the classic object review paradigm, letters are presented inside shapes during a task-irrelevant preview display, then the letters disappear and only the shapes move to previously unused locations, and then a single letter appears inside one of the shapes and participants are asked to name it. The central finding is that when the target was a letter that already appeared during the preview display, responses were faster when it reappeared inside the same shape as before, than when it reappeared inside another shape, an effect dubbed 'object specific preview benefit' (because it does not reflect a general priming-type benefit of seeing the same letter again, and is not tied to a specific location given that the shapes move during the connecting display). Most current studies use the modified review paradigm (Kruschke and Fragassi, 1996), which involves an explicit comparison of the preview and target letters (i.e., participants indicate whether the target letter already appeared somewhere in the preview display), but it is the basic finding of an object specific preview benefit that matters. Kahneman and colleagues suggested that this effect reflects a reviewing process, where each new object triggers the mandatory retrieval of a specific existing representation, in order to potentially update it with newly received input. It is this reviewing process that was argued to be faster when the target display matched the preview display in terms of the shape-letter pair, producing the effect. Object files were suggested to be temporary representations of objects that hold their changing features (Kahneman et al., 1992). As research in VWM emerged and developed, a wealth of evidence supported the claim, made in the object files framework, that as different features of the same object are encoded into VWM, they are held together in an integrated way, with a wide range of object-based benefits in behavior as well neural measures (e.g., Chung et al., 2023; Li et al., 2022; Luck and Vogel, 1997, 2013; Luria and Vogel, 2011a; Ngiam et al., 2024; Sone et al., 2021; Van Dam and Hommel, 2010; Vogel et al., 2001; Zhang and Luck, 2008).

Critically, when carefully considering a mapping between VWM and the external environment, the conclusion must be that object files revolve around the online representation side of the mapping (with the review process relating to how these representations are updated), while VWM's pointer system is the implementation of the mapping itself. This distinction was made explicit in earlier investigations of both VWM-pointers and object files (e.g., Kahneman et al., 1992; Pylyshyn, 2001, 2000): object files are not content-free (they can be seen as integrated VWM representations, what current conceptions usually refer to as the contents of a VWM-slot), and VWM-pointers do not themselves directly represent objects' features.

Recently, evidence for object-based compression in VWM supported renewed calls for the necessity of content-free pointers (Huang and Awh, 2018; Swan and Wyble, 2014; Wei et al., 2024; Yu and Lau, 2025a, 2025b). Additionally, novel use of EEG decoding has shown that when different stimuli are maintained in VWM, a stable signature of load can be extracted, which is independent of the specific feature dimension that is attended, and is sensitive not to feature-load but to the number of units people hold in mind (Jones et al., 2024a, 2024b; Thyer et al., 2022). While this content-free framework, centered around load decoding, agrees with more classic conceptions that VWM-pointers are not representing features, it diverges from the traditional views in a significant and critical way: VWM-pointers are treated as tokens that bind items to their episodic context (Awh and Vogel, 2025; for similar previous perspectives that build on evidence from other paradigms, see Bowman and Wyble, 2005; Kanwisher, 1987), instead of mapping to items in the environment. As such, this recently-suggested view is thus closer to the object file framework, while the correspondence mechanism itself, which is the focus of the present review, is theoretically distinct from the episodic representational content. Moreover, new evidence presented below (Section 4) directly supports the claim that the pointers and representations of VWM are empirically dissociable.

Finally, another line of evidence suggesting the necessity of a correspondence process revolves around updating information in VWM, i.e., modifying an existing VWM representation. As mentioned above, MOT findings demonstrate that VWM can update its representations to reflect dynamic spatial information (e.g., Drew et al., 2011), but updating is not limited to locations. People are able to continuously track objects through feature space: when two static overlapping stimuli continuously change their colors, spatial frequency, and orientation, participants still hold on to their individuated objecthood, producing object-based benefits (Blaser et al., 2000). In line with this, people can selectively update a feature (e.g., color) of one of the objects they represent in VWM (Kong and Fougnie, 2022; Lin et al., 2021). Another example is mental rotation, where a static image of an object is compared with some target object that potentially differs in its relative angle; the comparison can be carried out by mentally rotating the image in VWM (Ankaoua and Luria, 2022; Hyun and Luck, 2007; Prime and Jolicoeur, 2010). Furthermore, the same featural information can be maintained in VWM at several levels of compression, and the transition between them was shown to follow online interactions between items, at least under certain conditions. When items meet their VWM-representations can become compressed (i.e., chunked) so that they consume less VWM resources, and when previously-integrated items go their separate ways, their representations become no longer compressed (i.e., unchunked), now consuming as much VWM resources as independent items. This demonstrates that VWM can also update to reflect dynamic grouping cues (Balaban and Luria, 2015, 2016a; Luria and Vogel, 2014). Collectively, these findings establish the range of different changes an object undergoes which can be translated into its representation in VWM, via updating. Theoretically, like spatial updating in MOT, non-spatial updating requires some way of selecting and accessing a specific representation within VWM's workspace, which cannot be based on features because these features might change (Blaser et al., 2000); in fact, this very change might be the trigger for the updating process.[4]

3. Manipulating VWM's pointer system: VWM resetting

To recap, VWM only represents a subset of the dynamic external environment (because of its extreme capacity limit), but there must be a way to access each such representation when the corresponding real-world item changes. In other words, updating – whether with regards to locations, as in MOT, or for other aspects, as described in the previous section – depends on a continuous mapping between VWM representations and objects in the environment (via perceptual input), so that the appropriate VWM representation can be accessed when needed.

In recent years, we developed a new approach to study the dynamics of VWM's pointer system that hinges upon this theoretical idea (Balaban et al., 2018a, 2018b, 2019a, 2023; Balaban and Luria, 2017, 2019). Specifically, we postulated that if something disrupts the continuous mapping between VWM and the external environment, then updating should be impossible because access is denied. Instead, we proposed that VWM must reset, a novel process that can complement updating in terms of how VWM handles dynamic information. In resetting, the original unmapped representation is removed and replaced by a new representation of the modified input, along with a new valid mapping.

[4] Note that updating isn't necessarily limited to perceived change in the represented objects, and can happen in response to changes in internal interpretation, task demands, and so on (e.g., Balaban and Luria, 2016b). Naturally, these other forms of updating are more challenging to study, as they are more difficult to control and manipulate, and so almost all existing studies focus on updating triggered by external changes in some aspect of the represented items' appearance, which is also our focus here.

Identifying such a process can be harnessed as a window into the hidden workings of VWM's pointer system: situations that trigger resetting can be concluded to involve factors that are critical for the normal function of the correspondence mechanism.

Unlike previous research, this approach deliberately does not use a task like MOT, because it aims to find traces of VWM's pointer system beyond a spatial tracking context.[5] Instead, studies employed a regular VWM change detection paradigm, where participants had to retain the unique shapes of moving items for a same/different test. This means objects' movement can be manipulated in ways that are hypothesized to support different pointer system dynamics. Specifically, all objects started their movement as coherent units, but they then either continued to move cohesively or split into two halves. Regardless of the condition, the task was performed on shape-halves (i.e., only one of them potentially changed, and subjects' task was to report this) at their final post-movement location, making the movement completely irrelevant. The theoretical idea of a mapping between VWM and items in the external environment suggests that in the split condition, one pointer should support the representation of a single object during the cohesive pre-split movement phase, and two pointers are required after the split, for each of the two representations of the new objects (i.e., halves of the previous shape). But transitioning between the two states creates a correspondence problem: after the split, there are two independently-moving shapes, none of which matches the original whole shape, despite both stemming from the same single moving stimulus. We therefore hypothesized that VWM won't be able to update following the split, and instead the lack of correspondence should trigger a resetting process. This idea stands in contrast to what is expected if no pointer system exists for VWM, so that whenever some perceptual link is maintained between previous and present perceptual inputs (despite no longer corresponding to the same real-world object), VWM would go on updating the same representation (note that one additional possibility is that VWM's pointer system can maintain the mapping with one of the post-split items, a situation that will also allow for continuous updating; we return to this idea later). Probing VWM in real time allowed us to trace and identify the resetting process, which is derived from the premise of a pointer system in VWM.

Corroborating the theoretical hypotheses originating from the notion of resetting, two independent methods indicated the vulnerability of VWM in processing events that invalidate the correspondence. First, if an item is represented in VWM but without a valid mapping to the external environment, its representation should become inaccessible, meaning that it becomes impossible to compare the present perception of the item with the previous percept(s) of the same item, stored in VWM. To test this, we modified the classic change detection paradigm so that it probed participants' VWM when items were fully visible, instead of after a retention interval. Namely, in the 'online change detection' task, participants watched moving items that could change their shape during the movement (with no period where items are invisible; for evidence that the presence of a retention interval is not necessary for VWM involvement, see Tsubomi et al., 2013). This online change in a moving shape is normally very easy to detect, and indeed participants are at ceiling performance when the change happens in items that do not split. However, when the salient shape change happened in the splitting item and coincided with the separation, people struggled to report it (Balaban et al., 2018b; Balaban and Luria, 2017). Performance quickly recovered, and after 250 ms participants were at ceiling in detecting an online shape change, even when it happened to the separated item. Moreover, when the trial included a splitting item and a non-splitting item, changes during separation were perfectly detected when they happened in the non-splitting item (Balaban et al., 2018a). Given that attention likely shifts to the separating item, the fact that changes in another item in the display are easy to report also rules out an important alternative account of the cost: it is not the result of attentional capture by the salient splitting event, because that would predict a larger cost for unseparated items.

Second, if indeed VWM updating relies on the mapping in accessing representations, then without a mapping updating should be impossible. Consequently, disrupting VWM's pointers should create discontinuity in representational dynamics, as VWM discards the pre-disruption representation and starts anew. Evidence for this was found using an electrophysiological marker of VWM, specifically an Event-Related Potential (ERP) component named the contralateral delay activity (CDA; McCollough et al., 2007; Vogel et al., 2005; Vogel and Machizawa, 2004) that we now shortly introduce. CDA amplitude rises when more items are held in VWM, until it plateaus at a level that correlates with the individual capacity limit (for a review and meta-analy,see Luria et al., 2016). Many studies have validated the CDA as a specific index of VWM, demonstrating that it can be dissociated from a range of related but distinct factors and processes like eye movements (Kang and Woodman, 2014), spatial attention (Feldmann-Wüstefeld et al., 2018; McCollough et al., 2007), or the number of attended locations (Balaban and Luria, 2016b, 2016a; Ikkai et al., 2010; Luria and Vogel, 2014). The CDA is a difference wave calculated as a subtraction of ipsilateral from contralateral activity with regards to the attended side on each trial, and this lateralized approach makes the CDA insensitive to perceptual factors (e.g., Gao et al., 2011; Ikkai et al., 2010; Luria et al., 2010). The fact the epoch ends right before the test array appears means that the CDA is not contaminated by response-related factors (see Awh et al., 2007). Additionally, the CDA was shown to be insensitive to whether the items are removed for a retention interval or remain visible on screen (Carlisle et al., 2011; Drew et al., 2011; Luria and Vogel, 2011b; Tsubomi et al., 2013), meaning that it specifically tracks active maintenance in VWM, which is not limited to short-term memory tasks.

Different studies demonstrated that when VWM representations are updated, CDA amplitude rises or lowers in a monotonic way to reflect the new information load (e.g., Drew et al., 2013, 2011; Vogel et al., 2005), as is the case, for example, when two separate items join to form a group (Balaban and Luria, 2016b, 2016a, 2015; Luria and Vogel, 2014). Applying the same logic to an object that splits in two, if updating is possible, then the CDA should steadily rise to reflect the new item load as VWM smoothly transitions from representing a single item (the entire pre-split object) to representing two independent items (each half of the previous object, which now constitutes its own object). Critically, within the theoretical framework of a pointer system, such updating depends on a continuous mapping, and this mapping is disrupted by the split. Indeed, while the CDA in the split condition eventually reached the level of two independent items, before the rise there was a sharp drop in amplitude shortly after the split (Balaban et al., 2018b, 2019a; Balaban and Luria, 2017). Because a lower CDA amplitude is commonly interpreted as showing that less information is stored in VWM, while a larger VWM load was found towards the end of the trial, the transient drop cannot be accounted for by some form of continuous updating, which was the representation-modification process that was studied in VWM research until then. Instead, the drop suggested the presence of a novel process, revolving around the need to remove the pre-split representation, because it is inaccessible now that its supporting pointer is no longer valid, and reencode the post-split input (as indicated by the eventual rise in CDA amplitude).

Importantly, the CDA-drop does not directly reveal the dynamics of VWM's pointer system, but the downstream influence of a disruption to its mapping (i.e., resetting) on VWM's representations. The drop itself either reflects the removal of unmapped representations, or the reencoding of new representations from scratch (it should be noted that the contralateral and ipsilateral waveforms are similar to when the items are first presented and encoded; Balaban and Luria, 2019; see also Balaban

[5] The paradigms still highlight the dynamic aspect of VWM, either by using moving items or by changing the to-be-retained stimuli in different ways, thus encouraging some modification of the representations (i.e., updating or resetting).

et al., 2024; Friedman et al., 2024).

The behavioral and neural effects that follow a split, presented in Fig. 2, fit the claim that when the established mapping between VWM and the external environment is invalidated, VWM must reset. In support for the argument that the effects indeed reflect disruption to VWM's pointer system and not lower perceptual factors like the need to process a separation event or the change in set-size, both the behavioral cost and the CDA-drop are lacking if the halves are easy to individuate already during the coherent movement phase, for example when each shape-half is marked with a distinct task-irrelevant color (Balaban et al., 2018b, 2019a). This situation is extremely similar to the coherent object split in both perceptual factors and task demands, yet the individuation presumably allows the system to assign independent pointers to each shape-half to begin with, meaning the pointers are not invalidated by the split. Generally, not every perceptual change triggers resetting; as long as there is a valid mapping between each VWM representation and the corresponding external item, this mapping can be used for updating, even when the item undergoes large and/or abrupt changes, or the perceptual availability of it is modified (e.g., because of occlusion, large head movements, and so on). One recent example comes from a study that briefly flashed items during a VWM task, and found that this perceptual manipulation of a quick onset-offset, which should not interfere with the pointer system, resulted in a different CDA pattern, namely an early and short-lived drop effect that was dissociated from the resetting-drop (Friedman et al., 2025). Perhaps the most extreme manifestation of the claim that the correspondence can be maintained across large changes (as indicated by the absence of a CDA-drop) is found in the lack of resetting when items disappear for a ~1 s retention interval.

Furthermore, other events that should make the original mapping invalid also lead to similar disruptions, as indexed by a CDA-drop (Balaban and Luria, 2017; Friedman et al., 2024; Park et al., 2020). For example, several studies have used a change detection task without movement, where a stationary polygon appeared as the memory array. After a brief (50 ms) blank interval, the original polygon either simply repeated (as a perceptual control), was joined by another polygon at a different location which participants were asked to encode as well, or switched to a different polygon at the same location, in which case participants were asked to replace the original item. The results showed a drop following object-replacement (i.e., when the original item was no-longer task-relevant and was overridden), but not after addition (i.e., when the original item still had to be maintained). These findings demonstrate that factors like splitting, changing the set-size, movement, or visibly showing some disruption, are neither sufficient nor necessary for a resetting process, pinpointing pointer invalidation as the critical trigger. It is also important to note that the driving factor behind resetting isn't surprise: The behavioral cost and the CDA-drop survive dozens and even hundreds of repetitions, happen when the critical event is highly probable throughout the experiment, and can even be observed for events that are perfectly predictable (Balaban et al., 2018a, 2018b, 2019a, 2023; Balaban and Luria, 2017; Friedman et al., 2024).

Together, this marks the behavioral and electrophysiological indexes of resetting as valuable tools for studying VWM's pointer system itself, by manipulating it. Importantly, the magic-like changes that this line of research has used to trigger resetting are not argued to happen often in day to day situations; most of the time the environment changes in a way that likely allows the mapping to be maintained, with VWM representations being updated. Yet, the extraordinary conditions that lead to resetting uncover the hidden workings of VWM's pointer system by revealing factors that are critical for its normal function. We next review some important results of applying this approach.

4. Insights from manipulating VWM's pointer system

A key component of early conceptions of pointer-like processes is that the mapping 'layer' is distinct from VWM's representations (e.g.,

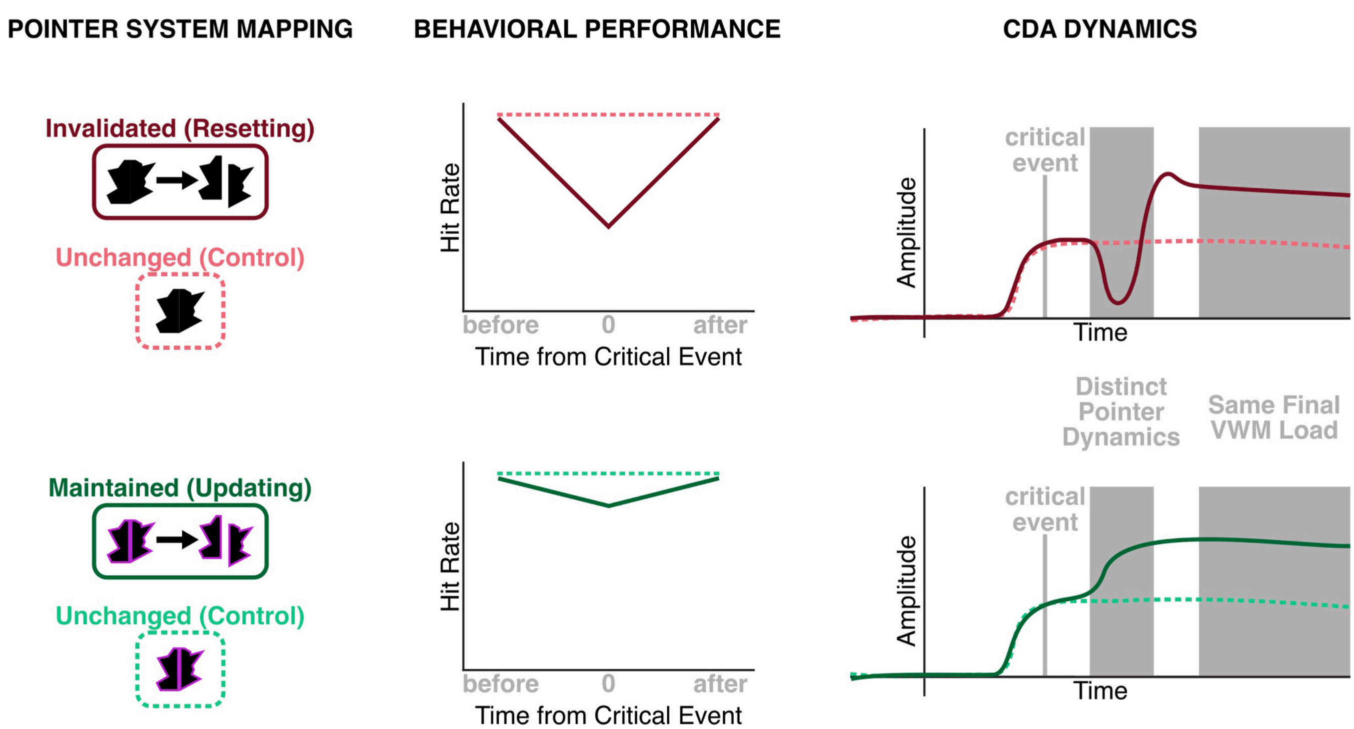

Fig. 2. A schematic **overview of the patterns found for resetting (top) vs. updating (bottom) of VWM representations.** When the mapping between the external environment and VWM content is somehow disrupted (here, because a coherent object, which was presumably supported by a single pointer, splits in two), VWM's representations become inaccessible and it must reset. During resetting, behavioral performance demonstrates that people are largely blind to salient changes in the items they are trying to maintain in VWM, and the CDA drops, suggesting that new representations had to be reencoded anew. Very similar situations that do not disrupt the mapping (here, adding a frame around each half already during the joint movement, which encourages forming two individual pointers) are characterized by a reduced behavioral cost and a monotonic change in CDA amplitude.

Pylyshyn, 2000). Often each pointer will map onto the contents of a single VWM-unit (i.e., the contents of one 'slot'), so empirically dissociating contents from mapping is challenging (for example, a decoded multivariate EEG signal that varies with item load in VWM might index either pointers or the representational content itself; Jones et al., 2024a, 2024b; Thyer et al., 2022). Yet it is theoretically crucial to disentangle pointers from the representations that rely on them, and it is supposed to be possible to create situations where a strong ensemble of objects taxes VWM similarly to a single simple object, but is supported by *multiple pointers*.

The first evidence for this distinction comes from the fact that similar situations that diverge in terms of resetting versus updating can still have the same CDA amplitude before the critical event (Balaban et al., 2018b, 2019a). For example, a uniformly black polygon and a bicolored polygon both have low CDA amplitudes prior to splitting, but after the split there is a drop (signaling resetting) in the uniform condition and a steady rise (signaling updating) in the bicolored condition. This pattern suggests that before the split, both types of full-polygon stimuli were chunked in VWM, yet this chunking was supported by a single pointer for uniformly-colored stimuli and by two independent pointers for bicolored stimuli, due to the distinctiveness of the colors.

A recent study (Balaban et al., 2023) provided direct evidence for this, using shapes that moved independently, met to form compound shapes that moved together, and reseparated. Each shape initially had a unique color, and this was kept throughout the trial in one experiment, but in another the colors changed to a uniform black when the shapes met. The task was a shape change detection paradigm, and colors were irrelevant, as were all movement cues. Both experiments demonstrated a reduction in CDA amplitude after the meeting, suggesting that regardless of the colors, the joint movement was effective in encouraging compression of the compound shape into one VWM-unit. Both experiments also had a higher amplitude at the end of the trial (after the items moved independently again), showing that despite the previous interaction, each independently-moving shape was now held in its own VWM-unit. Importantly, this rise was monotonic in the experiment where unique colors were kept, but was preceded by a resetting-drop in the experiment where the shapes turned black from their meeting onward. This means that the apparently similar chunking (during the joint movement) and un-chunking (at the end of the trial) in VWM actually reflected different pointer system dynamics. In both cases the number of moving shapes (regardless of color) transformed from two to one and back to two, and the number of VWM-units (indicated by the CDA amplitude outside the resetting time-window) followed this in both experiments. In contrast, the number of objects that were implied to exist in the scene, based on color and motion cues combined, was different between the two experiments. When unique colors were presented throughout, the shapes were presumably interpreted steadily as two objects across all movement phases. In the experiment with changing colors, however, the objecthood changed as well, such that the scene was parsed into two objects during the initial separate motion phase, then only one object when the now-black stimuli moved together, and back to two objects after the split. Critically, the lack of resetting in the first case and its presence in the second case demonstrate that the number of VWM-pointers follows not the number of VWM-units, but the number of individual objects.

The results suggest that each pointer maps to a different object even when all the representations of several such objects are compressed into a single VWM-unit (via grouping). It is therefore vital to treat pointers as distinct from the VWM-units they support. This stands in contrast to some recent frameworks (e.g., Awh and Vogel, 2025), which accept that pointers are content-free in the sense that they don't directly represent featural information, but do not distinguish between VWM-load (i.e., 'slots') and the pointers that support the stored information.

The dissociation between content and mapping bears important consequences not only on our understanding of VWM's pointer system, but also on that of information compression (chunking) in VWM. Specifically, it appears that there are at least two distinct processes of VWM integration, with two different pointer system dynamics (Balaban et al., 2023; see also Balaban and Luria, 2016a; Luria et al., 2016). The first process, 'object-unification', involves binding multiple features of an object and compressing them into one VWM representation, which is supported by a single merged pointer. The second process, 'grouping', involves integrating several unique objects and maintaining them in one VWM-unit, but here each object still keeps an independent pointer, which allows the objects to also be easily ungrouped if and when appropriate. A recent study (Lando et al., 2025) extended this claim, showing that it holds not only for ad-hoc sets of items, but even for strong visual Gestalts. Specifically, the study used three Pacman shapes that formed a coherently-moving Kanizsa triangle, which was compressed in VWM, as seen from a lower CDA amplitude than that of a random array of Pacman shapes moving independently. When the Pacman shapes changed trajectory, so that the illusory triangle was destroyed, the grouping was disrupted, resulting in a higher CDA amplitude, but no resetting was triggered, as seen from the lack of a CDA-drop. In contrast, when just half of one Pacman changed trajectory and left the group, effectively splitting the item in two, there was a resetting process, signaled by a CDA-drop, despite the illusory triangle being largely intact. This pattern is in line with the idea that (at least under the tested conditions) even a strong group is not assigned its own VWM-pointer; otherwise, a resetting process would have followed the destruction of the Kanizsa. Moreover, the results demonstrate that grouping does not override the pointers of the member objects; otherwise, no resetting would have happened when an object splits without completely destroying the Gestalt.

The different mechanisms in object-unification and grouping (see Fig. 3) could explain why situations that can be classified as the later sometimes produce imperfect behavioral benefits, take time to fully integrate, and are more sensitive to context (e.g., Balaban and Luria, 2016b; Luria and Vogel, 2011a; Wheeler and Treisman, 2002), which might account for the mixed results in the rich literature on VWM integration. This demonstrates the ability to use VWM's pointer system as a separate cognitive structure, and the potential importance of such construal.

Another important attribute of pointers regards the 'other end' of the mapping, that is, how they are assigned to the external environment (as mediated by perception). A continuous perceptual stream can be carved out in different ways, and so we next consider whether VWM's pointer system operates in a spatiotemporal, featural, or object-based manner. These three factors are confounded when an object splits in two, because this simultaneously disrupts spatiotemporal continuity, changes the features in the task-relevant dimension which was shape, and destroys a coherent object. One study (Balaban et al., 2019a) targeted this question by using a color task, where an object splitting did not change the task-relevant dimension (the colors were simply duplicated, which does not affect VWM performance; Gao et al., 2011). If the mapping is based on task-relevant features, no resetting is expected when people monitor only the colors, but the CDA did drop, ruling out a featural account. This also goes against an interpretation of resetting as reflecting not pointer-invalidation but only a difficulty in pointer-reassignment, because it should be very easy to simply remap to each rectangle or keep the original mapping 'attached' to one of them. Yet the results still cannot distinguish between objects and a unitary spatiotemporal trajectory. To dissociate the two factors, a thin frame was added around each pre-split half of the square (i.e., rectangle). Now there was still a single spatiotemporal trajectory pre-split and two afterwards (all location information was held constant), but the objecthood cues changed such that each pre-split stimulus could be construed as two separate objects. If pointers are assigned to continuous spatiotemporal trajectories, this situation should also result in a resetting process after the split, but no drop was observed (see also Balaban et al., 2018b). Together, the results suggest that although features and locations obviously play a role in the mapping, as they indicate what part of

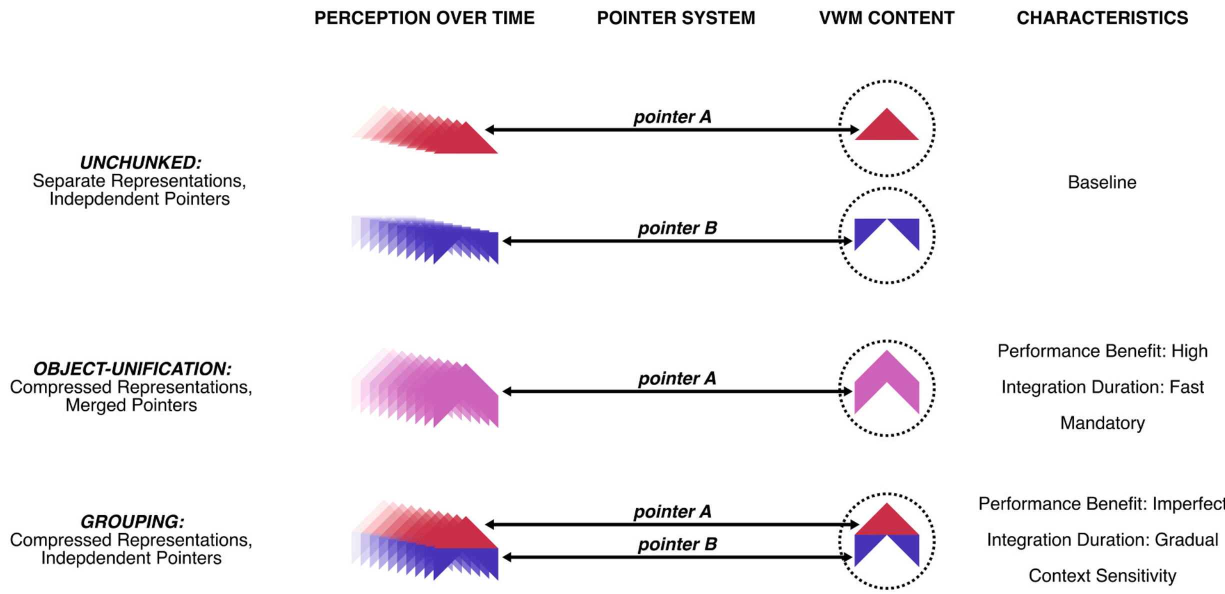

Fig. 3. Different relations between the number of VWM-pointers and the number of representational-units in VWM. In the most basic case (top), each simple item in the world is represented as a single object in VWM, and this representation is supported by a single pointer. Even complex items can be held in a single VWM representation that is supported by a single pointer (middle), through the process of *object-unification* that merges an object's different features and/or parts. But compressing the representations of several objects into one VWM-unit (bottom) when each object is still easily individuated (here, due to unique colors) does not involve fusing the pointers. Instead, in this *grouping* process VWM's pointers remain independent. This situation provides important evidence for the dissociation of VWM content from the mapping that supports it.

perception belongs to a given object, VWM's pointer system is object-based (see also Swan and Wyble, 2014).

This emphasis on coherent objects also helps explain an asymmetry in pointer system dynamics, where splitting one object in two triggers resetting, but when two previously-independent objects meet and start moving together, their potential integration is handled via uninterrupted updating (Balaban et al., 2023). The mapping between VWM and the environment revolves around individuation: it keeps track of the identity of each represented object, but only in an indexing sense (analogous to linguistic demonstratives like "this versus that"), as opposed to storing the specific features the object has. Through the lens of individuation, it is clear why objects meeting and moving together is not simply split-in-reverse (despite the perceptual sequence being just that): one cannot track less than a single unit, but a single unit can be very complex. In other words, two objects that strongly interact can become just one object, while half of a previously-coherent object cannot remain something unidividuated but must also be simply one object (see also Balaban and Luria, 2015).

Beyond the lab, objecthood has a highly important real-world meaning, whereby concrete objects behave in certain unique and predictable ways (e.g., the movement of rigid objects differs from that of piles of non-rigid substances), but does this have any implication for VWM's pointer system? A recent study (Balaban et al., 2024) suggested that in maintaining the correspondence, VWM's pointer system might rely on high-level principles that govern the dynamics of physical objects (see also the notion of "proto-objects"; Pylyshyn, 2000). This work used a VWM task with stimuli inspired by developmental studies (e.g., Baillargeon et al., 1985; Spelke, 1990; Wynn, 1992), namely 3D animations of physical scenes with one or two items that cross a stage as a screen comes up and down in front of them, hiding them from view before they come back out. Aside from 'possible' conditions where the objects moved in a normal way, there were two physically impossible conditions, with an object magically being created behind the occluder (i.e., a single object entered but two came out) or magically vanishing (i.e., two objects entered but only one came out). Note that here, the critical events happen when objects are hidden from view, making them extremely non-salient. Nonetheless, a drop in CDA amplitude indicated that these violations of object permanence disrupted VWM's pointer system, despite involving the most minimal perceptual information (the vanishing event only included an item failing to be observed, meaning something that should have happened but did not), or new objects that were not previously tracked (when another object was 'created' but nothing happened to the previously-monitored object). This demonstrates that the mapping between VWM and the external environment takes into account the commonsense physics of the scene. Here, 'commonsense' means that people are not explicitly and consciously solving the precise mathematical equations describing all of the objects and forces in the scene, but instead emploing some implicit intuitive mode of physical reasoning (see, e.g., Fischer et al., 2016; Kubricht et al., 2017; Ullman et al., 2017). Corroborating this conclusion, in another experiment no resetting process was observed when the violations were explained away by adding a small black rectangle behind the occluder, presented to participants as a hole in the floor that objects can climb out of or fall into (though again, the screen hid the critical events, making the perceptual input identical to the previous experiment), pinpointing high-level physical expectations as the driving force behind the findings.

The idea that pointers are sensitive to intuitive physical expectations (see also Balaban and Ullman, 2025b; Lau and Brady, 2020) helps reunite previous resetting findings (see Fig. 4), because all of the events that were found to disrupt VWM's pointer system actually involve some violation of core physical knowledge of the type pre-verbal infants already possess (Spelke, 2022; Spelke and Kinzler, 2007): coherence in split events (e.g., Balaban and Luria, 2017), object permanence in switch events (e.g., Friedman et al., 2024), and kind identity in abrupt featural change (e.g., Park et al., 2020). It is even possible that some phenomena described in the developmental literature after violations of expectations could reflect a resetting process (see also Carey and Xu, 2001). For example, babies struggle to keep track of the basic attributes (like overall quantity) of objects if these objects split (Cheries et al., 2008), and sometimes seem to hold no expectation at all about how many objects are present after physical violations (Stavans et al., 2019).

Characterizing VWM's pointer system as a process governed by physical objects echoes the central claims of the object-based FINSTs framework (Pylyshyn, 2001, 2000), with the findings raising two

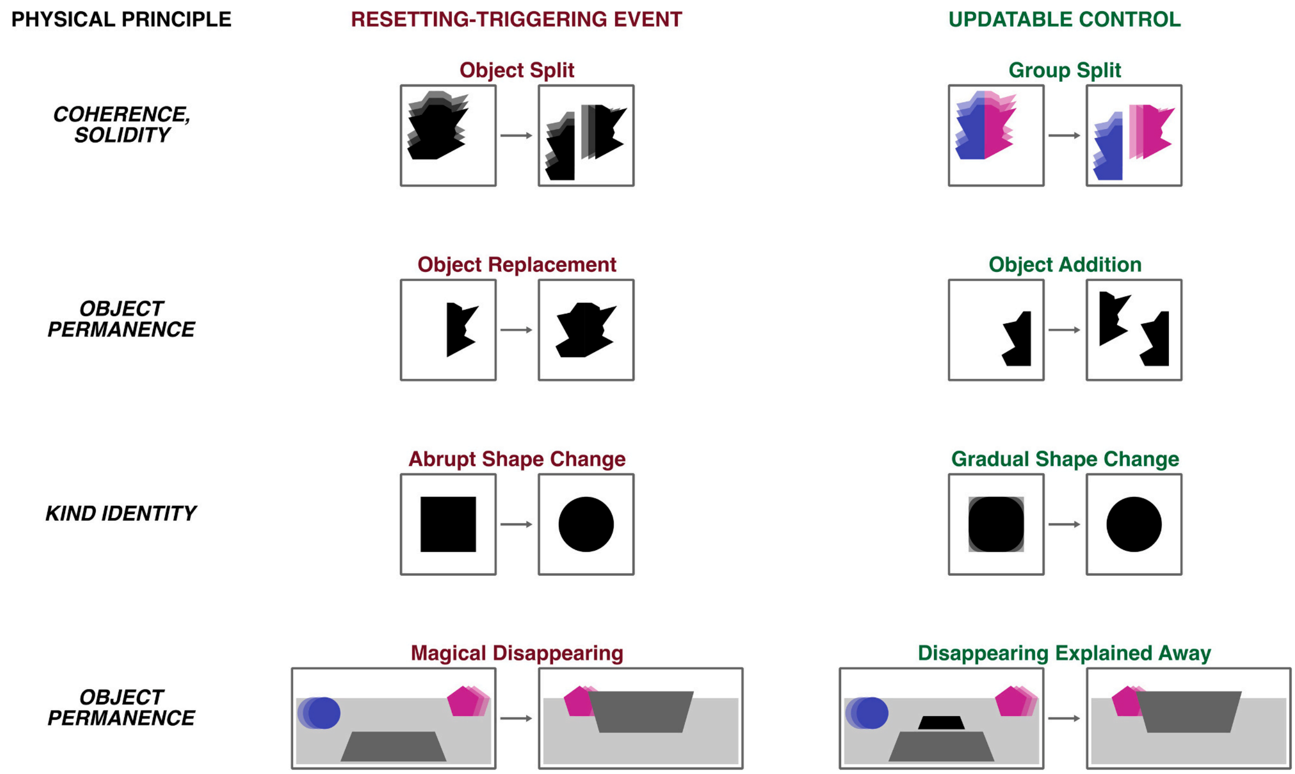

Fig. 4. An overview of the connection between core physical knowledge and VWM's pointer system. Previous studies, mentioned in the main text, described several types of events that trigger a resetting process (middle column), meaning they disrupt the mapping between VWM and the external environment, while perceptually similar control events allow VWM to go on accessing and updating its representations (right column). Each of the resetting-triggering events can be described as violating a physical principle (left column) that developmental and comparative studies have shown to be fundamental to core knowledge, suggesting that VWM's pointer system is deeply connected to commonsense physics.

important clarifications regarding how VWM pointers are maintained. One issue is that pointer assignment is not restricted to bottom-up 'grabbing' based on saliency, as was previously argued (see also Holcombe, 2023). This is because violations of physical expectations invalidate the mapping even when they involve minimal change to the perceptual input, while perceptually-identical situations that are given a different explanation allow the mapping to hold (Balaban et al., 2024). It has also been recently demonstrated that events that are unseen but merely inferred can trigger resetting (Friedman et al., 2025), and that when mapping-disruption events become very frequent VWM's pointer system begins to reset even for events that in other contexts allow the mapping to remain valid (Friedman et al., 2024).

Another important point is that resetting cannot be boiled down to only violations of spatiotemporal continuity, even in a broad sense, meaning that treating VWM's pointers as spatiotemporal (e.g., Thyer et al., 2022) is potentially misleading. Critically, identical spatiotemporal information was found to trigger different pointer system processes in VWM (i.e., resetting vs. updating) as a function of the physical interpretation of the scene (Balaban et al., 2024). Additionally, one study reported resetting following an abrupt color change, with no manipulation of spatiotemporal information (Park et al., 2020). Finally, a Gestalt can also be unified in space and time, but if its forming members are individuated, it won't be assigned a VWM-pointer, unlike when a similar stimulus is interpreted as a single object (Balaban et al., 2023; Lando et al., 2025). Thus, spatiotemporal cues are an extremely important aspect of objecthood (arguably the most important one), but it is physical objects that are the currency of VWM's pointer system.

As mentioned above, the content of VWM is separate from the mapping that supports that content, but given that pointers can be considered the infrastructure of VWM's representations, the fact that these pointers are object-based likely influences aspects of the representations as well. While it has been repeatedly demonstrated that representing features as part of a single object boosts VWM performance, in terms of accuracy as well as neural resources (e.g., Luck and Vogel, 1997; Luria and Vogel, 2011a; Sone et al., 2021), leading some researchers to posit an object-based structure to VWM contents, others have claimed that VWM representations are best understood as built around feature load, regardless of the objects these features belong to (e.g., Bays and Husain, 2008; Ma et al., 2014). An object-based pointer system in VWM puts strong limitations on this debate, as it shows that the representations of different individuated objects in VWM are supported by independent pointers, creating clear boundaries between them.

5. Open issues and paths for future research

In this final section, we mention several questions that we see as especially important for a more complete understanding of VWM's pointer system. First, while processes that rely on VWM's pointer system, most notably VWM maintenance and spatial tracking, are known to be extremely limited in their capacity (usually estimated as around 3–4 simple items' worth of information; e.g., Alvarez and Franconeri, 2007; Balaban et al., 2019b; Cowan, 2001), the capacity limit on VWM's pointers per se remains unclear (see also Holcombe, 2023), and this basic attribute of the system should be examined. One possibility, sometimes implicitly assumed yet currently untested, is that the number of pointers constitutes the limiting factor in downstream online information processing in VWM. Yet, even if the two 'levels' have similar limits, the relationship between their capacities is not given and deserves further investigation.

A second issue, which also touches upon capacity limits, revolves around information compression in VWM. The work surveyed here suggests that grouping, i.e., compressing the representations of several items into a single VWM-unit, is not mediated by the pointer system, because each object can still maintain an independent pointer (Balaban et al., 2023; Lando et al., 2025). But this raises the question of what does support grouping in VWM. There is also the question of whether a group of objects can sometimes get its own VWM-pointer (e.g., due to increased familiarity, task demands, etc.). And, given that grouping is often studied as a way of circumventing VWM's capacity limits, if it involves maintaining more VWM-pointers, what would this entail regarding the nature of capacity limits for VWM representations and pointers?

Third, current investigations of VWM's pointer system concentrate only on discrete objects or ensembles of objects. This is not unique to the study of the mapping itself, but also more broadly for VWM research, where the representations being studied are almost solely of these types of stimuli, which are considered the central focus of everyday cognition. The research presented here found that when an object is represented in VWM, a pointer is assigned to that object and not its features or any group it belongs to. But an interesting question for future research is how other stimuli, such as non-rigid materials (e.g., fluids) or the boundaries between objects, are handled, in terms of both the representations and VWM's pointer system. This is especially important given the newly-established role of intuitive physics – which handles such diverse types of entities in distinct ways – in these aspects of everyday cognition (Balaban et al., 2024; Balaban and Ullman, 2025b; Lau and Brady, 2020).

A fourth issue is that the metaphor of content-free pointers, borrowed from computer science, has been suggested in other similar, though not identical, contexts. Most closely related is the hypothesis of a pointer system that maps two different parts of working memory (Cowan, 2019; Norris, 2017; Ruchkin et al., 2003). The idea is that all of the maintained information is presumably held in activated long-term memory, while a subset (perhaps only a single item; Oberauer, 2002) is in the current focus of attention, with pointers connecting these levels such that each pointer is a place holder for a potentially complex representation in activated long-term memory. A central theoretical and empirical question is to what extent the two notions of VWM-related pointers (from the focus of attention to activated long-term memory, and between VWM and the external environment, as mediated by perceptual input) refer to the same process versus just happen to use the same name.

A fifth, somewhat related, question, concerns resetting, i.e., the process triggered by a loss of the mapping between VWM and objects in the world, which stands in contrast to updating, the gradual modification of representations based on a valid mapping. Across varied domains, similar processes have been described, involving discontinuity as an existing representation is replaced by a new one. For example, Piaget's famous theory of the development of thinking (Piaget, 1952) included two complementing processes, assimilation and accommodation, meaning adding a new element to an existing schema, versus changing the schema itself or even creating a new one. Another example comes from Gernsbacher's structure building framework in linguistics (Gernsbacher, 1997, 1991), where sentence comprehension advances by laying a foundation and developing the structure by continuously mapping incoming input to previously comprehended information, but if this input is not coherent with the existing mapping, a shifting process is initiated, where foundations are laid for a new structure along with a new mapping. These processes resemble the resetting-updating dichotomy suggested in VWM, but it remains an open question whether there is indeed any underlying joint foundation, or whether instead the similarity is only on the surface.

Sixth, there are aspects of the VWM resetting process that are yet to be understood. One of the central issues revolves around the faith of unmapped representations: are they only inaccessible for further use after resetting, or are they completely wiped out from VWM, even with regards to the pre-resetting encoded information? A related issue is whether every type of removal from VWM reflects resetting, like when a representation of one item is actively replaced with a representation of a different item (Balaban and Luria, 2017; Friedman et al., 2024), or whether more 'passive' removal of information from VWM (e.g., due to decay) involves a different process.

Finally, a fundamental issue for any full theory of VWM-pointers is how best to describe this cognitive component, when moving from the computer science metaphor to the mental equivalent. A pointer is a specific type of variable, and while the content-free aspect of it is assumed as a defining characteristic of current VWM studies of the pointer system, and has a clear cognitive meaning, other aspects do not necessarily hold. What are the neural and computational underpinnings realizing the mapping between VWM and the external environment (e.g., are VWM-pointers maintained and re-established via computations related to intuitive physical reasoning, as implied by recent findings)? Our hope is that as more cognitive scientists take on VWM's pointers as a focus of their research, new answers – as well as modified questions – will present themselves.

Declaration of Competing Interest

The authors declare no conflict of interests.

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Data availability

No data was used for the research described in the article.

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