Object persistence explains event completion

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Abstract:

Our minds consistently distort memories of objects and events. Oftentimes, these distortions serve to transform incoherent memories into coherent ones, as when we misremember partial events as whole ("event completion"). What mechanisms drive these distortions? Whereas extant work shows that representations of causality, continuity, familiarity, physical coherence, or event coherence create memory distortions, we suggest that a simpler and more fundamental mechanism may be at play: object persistence. Merely seeing an object take part in an event can create a persisting memory of its presence throughout that event. In 8 pre-registered experiments (N=317 adults), participants performed a simple task where they watched an animation, then chose whether or not a frame from the animation contained an object. Participants falsely remembered seeing an object when it was not there (E1). These effects persisted in the absence of causality (E2), continuity (E3), event familiarity (E4), object familiarity (E5), even when the events violated physical laws (E6), and when the events themselves were not coherent (E7). However, the effect disappeared when we abolished object persistence (E8). Thus, object persistence alone creates rich, enduring, and coherent representations of objects and events.

Keywords

event cognition, event perception, memory distortions, object persistence, object representations

Materials: https://osf.io/pfxud/

In press, Cognition

Introduction

Memory is not perfect. Oftentimes, we *forget*, failing to recall the features of an object we saw or an event we experienced. We also *distort*, recalling something as different from what it was or when it occurred. For example, we ‘play forward’ the motion of moving objects, misremembering them as further along their paths than they really were (*representational momentum*; Freyd, 1983; Freyd & Finke, 1984; Hubbard, 2005; Hubbard, 2006; Hubbard, 2017; Hafri et al., 2022); we ‘extend’ the boundaries of scenes, filling in information that was not there (*boundary extension*; Intraub & Richardson, 1989; Hafri et al., 2022); and we ‘complete’ events that are incomplete, thinking we saw the start of a causal event when we in fact did not (*event completion*; Strickland & Keil, 2011; Kominsky et al., 2021). Such distortions happen quickly and automatically, and their behavioral traces illuminate aspects of the mechanisms and functions of memory more broadly. For this reason, much work characterizes how, when, and why we distort memories. Although such distortions are numerous and well-characterized, a key question regarding their nature remains poorly answered: What explains these phenomena?

The mechanisms underlying memory distortions like event completion are unclear, though a variety of different explanations have been provided. For example, some suggest that spatiotemporal cues may drive these distortions over and above object-intrinsic features. Such cues include causality — which may lead us to fill-in missing information about an event (Kominsky et al., 2021; Hubbard & Favretto, 2003) — and continuity — which may affect how we individuate objects (Spelke et al., 1995; Xu & Carey, 1996; Kibbe & Leslie, 2019; Li et al., 2023). Others suggest that, more broadly, the physical properties of an object or the context in which it is presented may affect how we represent — and then remember — the object (Spelke et al., 1992; Biederman, 1981; Scholl, 2007). These explanations arise not only at the level of objects but also at the level of events; continuity, familiarity, and coherence may drive key aspects of event perception (Zacks & Swallow, 2007; Zacks et al., 2007; Hubbard, 1993; Baker & Levin, 2015; Zacks, 2020; Radvansky & Copeland, 2006; Papenmeier et al., 2019). Many of these proposed cues emerge not only in visual processing but also in language (see, for example, Papafragou et al., 2008; Trueswell & Papafragou, 2010; Bunger et al., 2013; for review, see Ünal & Papafragou, 2020; Ünal et al., 2021). In other words, each of the aforementioned cues substantially affect how we process objects and events; thus, each cue appears to be a viable candidate explanation for what causes event-based memory distortions.

But what if such representations are not even necessary for memory distortions? Perhaps these cues do not cause memory distortions, but rather modulate the strength of an already-present effect. Empirical evidence supports this suspicion regarding some cues. For example, various memory distortions arise even in novel and entirely unfamiliar events, suggesting that familiarity itself does not drive observed effects: Event completion occurs not only for naturalistic stimuli depicting real events (e.g., a person kicking a soccer ball), but also for synthetic stimuli generated with animation software (Kominsky et al., 2021). Representational momentum occurs not only for familiar events that unfold forward in time (e.g., an ice cube melting into a puddle), but also for unfamiliar events that unfold backward in time (e.g., a puddle 'un-melting' into an ice cube; Hafri et al., 2022). Perhaps the greatest puzzle of this kind arises in the initial event completion findings (Strickland & Keil, 2011): Though rates of event completion were highest for continuous events with causal implications, participants completed events at a high rate even in the absence of these cues. How do we reconcile such ideas?

Here, we propose that a simple cue may account for these distortions: object persistence (for review, see Scholl, 2007; Scholl & Flombaum, 2010). We suggest that seeing an object creates an enduring memory of that object, leading the mind to fill in its presence after the object disappears. We use 'object persistence' to mean the existence of a mental pointer to an object that persists over time. In other words, much like how an object-file is often thought to contain spatiotemporal features to 'label' the file and surface-level features inside the file (Flombaum et al., 2009; Green & Quilty-Dunn, 2021), we conceive of 'persistence' as the continued existence of that file within a given event representation. (Note how this differs from other notions of object persistence which refer to additional physical features, such that a disruption of continuity implies a disruption of persistence; Baillargeon, 2008. See additional discussion of this issue in the *General discussion* below.)

We demonstrate that persistence is so powerful that it creates these distortions in the absence of each of the aforementioned cues. Persistence appears to provide the most salient index to object-files in events; other features seem only to modulate those files. In other words, we suggest that persistence may be the simplest — and strongest — explanation for event completion. Although this explanation may feel reductionist, we show that it a) dovetails nicely with findings from developmental psychology and animal cognition, b) implies rich qualities of object representations, and c) may serve as a useful explanation for other memory distortions too.

The present experiments: What creates event completion?

Here, we conduct 8 pre-registered experiments that suggest object persistence may be the simplest explanation for 'filling-in' effects in event cognition. In each experiment, participants watched an animation of an object moving towards a soccer goal (Figure 1A). The video displayed a side-view of an object, followed by a front-view of the object entering the goal. Crucially, we manipulated the presence of the object in each half; some animations contained an object in both halves of the animation, some contained an object in only one half of (but not the other), and some contained no object at all (Figure 1B). Upon a video's completion, participants saw a brief box-scrambled mask, and then they were presented with two frames. One frame contained an object, and one did not. Participants reported which of the two frames they remembered seeing in the video.

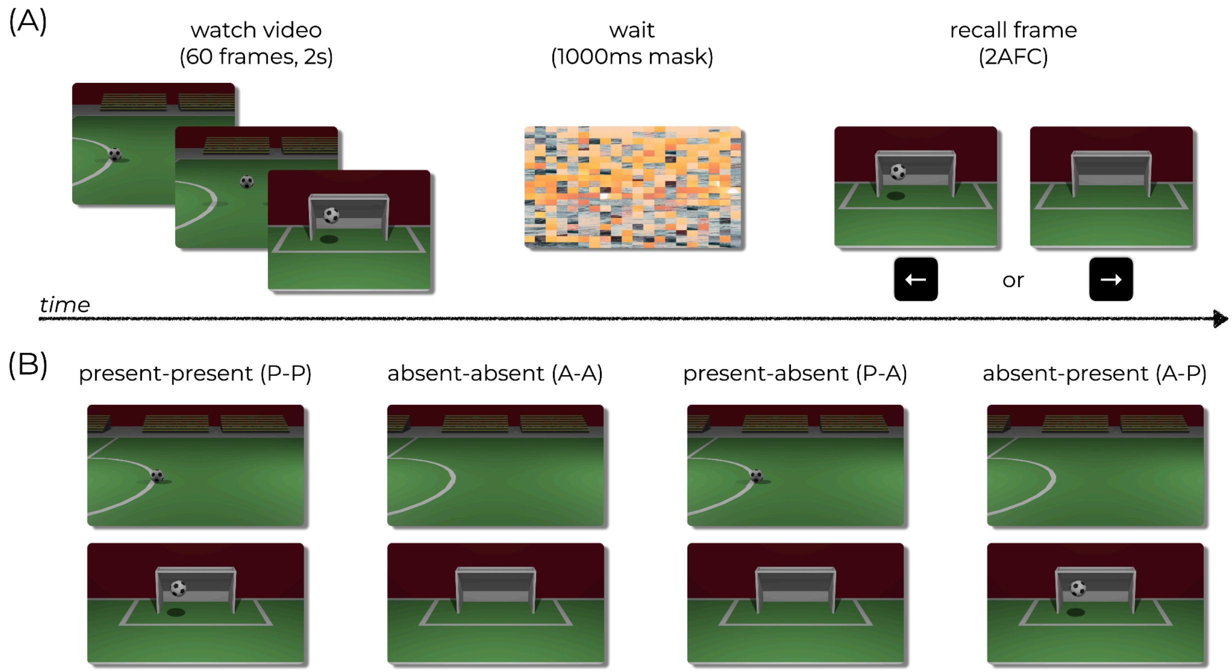

Fig 1. Schematic depiction of our experiments and stimuli. In all experiments, participants watched videos of events created in Blender. We manipulated the presence or absence of an object in these animations. (A) On each trial, participants watched a video. The video was masked upon completion, after which point participants said which of two frames they saw in the video. One option contained the object, and one did not. (B) In each video, the object could be either present or absent in either half. We were interested in asking whether the ball's presence in one part of the video would lead participants to fill in its presence in another part of the video. Interested readers may view all experiments at https://perceptionstudies.github.io/persistence.

We asked whether seeing an object in one half of the video would lead participants to think they saw the object in the other half of the video, even if it was not there. This would be evidenced by high false positive rates on videos where the object was present in one half and absent in the other. To ensure that any observed distortions were not the result of an object-presence bias, we included videos which did not contain an object in either half (where an object-presence bias would lead to similarly high false positive rates). Additionally, to ensure that any distortions were not the result of inattention or poor memory, we included videos which contained an object in both halves (where inattention or poor memory would lead to low accuracy more broadly).

In Experiment 1, we found that for ordinary events (i.e., events with causal agents, continuous motion, etc.) participants filled-in the presence of the previously seen object. With this distortion in hand, we used the same paradigm and systematically removed several possible cues in 7 follow-up experiments. Specifically, in Experiment 2, we removed the agents from these events (disrupting causality); in Experiment 3, we shuffled the frames of the videos, such that the ball's motion was discontinuous (disrupting spatiotemporal continuity); in Experiment 4, we played the videos in reverse (disrupting both causality and event familiarity); in Experiment 5, we added trials where the object was a monkey instead of a soccer ball (further disrupting event familiarity by including unexpected objects); in Experiment 6, we added a wall to the videos that would make the event physically impossible (disrupting physical coherence); and in Experiment 7, we rendered events where each half composed a different context or 'room' (disputing event coherence itself; Figure 2A). The observed memory distortion survived each one of these manipulations. Thus, these cues alone were unable to account for our observed event completion effects.

Finally, in Experiment 8, we added trials where the object in the probe differed from the object in the video, thereby violating object persistence (Figure 2B); in other words, filling-in the object here would require a pointer to a different object-file. This manipulation removed the filling-in effect. Without persistence, the distortion no longer existed. Together, these experiments suggest that object persistence may be a fundamental part of explaining memory distortions like event completion.

All experimental designs were pre-registered, as were sample sizes, exclusion criteria and analysis plans. These pre-registrations — along with data, experimental code, analysis scripts, and the Blender files used to render our animations — are available in our OSF repository, which can be found here (https://osf.io/pfxud/). Interested readers may perform our experiments — exactly as participants saw them — on our guide page here (https://perceptionstudies.github.io/persistence).

Experiment 1: Distortions for normal events

Does the mind fill-in the presence of objects given minimal exposure? In our first experiment, we asked whether we could induce event completion effects for simple events. Suppose you see a person kick a soccer ball. You then see a goal — presumably the goal towards which the person was kicking the ball. However, no ball is in fact shown approaching the goal. If probed on the presence or absence of a soccer ball near the goal, would you falsely remember seeing a ball? In Experiment 1, we asked this question with regards to ordinary events.

Method

Participants

We recruited 40 adult participants from the online recruiting platform Prolific (for a discussion of the reliability of this subject pool, see Peer et al., 2019). All experiments used this sample size of 40 participants, and we pre-registered this choice (along with analysis plans, designs, etc.). This sample size was chosen to be approximately equal to what is used in similar studies (e.g., Strickland and Keil, 2011; Hafri et al., 2022).

Stimuli and Procedure

We rendered animations of simple events in Blender (v4.0.2). All animations contained 60 frames, and were presented to participants at 30 frames per second. The first 30 frames of each video showed a side-view of a soccer field with a ball on the ground. The ball was then launched (either with a low shot that rolled along the ground, or a powerful shot that sailed through the air), either by an agent or on its own. The last 30 frames of each video depicted a front-view of a goal on the soccer field, with the ball approaching. Sometimes, there was a goalie agent that dove to try and save the shot. The soccer ball was either present or absent in each half of the video. For example, the ball could have been present in both halves of the video ('present-present', or 'P-P'), absent in both halves of the video ('absent-absent', or 'A-A'), present in the first half but absent in the second half ('present-absent', or 'P-A'), or absent in the first half and present in the second half ('absent-present', or 'A-P').

We generated 16 unique videos by matching all combinations of: 4 soccer ball presence conditions (present-present, absent-absent, present-absent, absent-present) × 2 shot types (low shot, high shot) × 2 agent types (kicking agent but no goalie agent, goalie agent but no kicking agent).

Participants were instructed to watch the videos closely. We told participants that we would test their memory for each video. Videos were presented at 704 × 396 pixels in the participant's web browser. Upon each video's completion (after 2 seconds), a box-scrambled mask (chosen randomly from a set of 7 masks we created) appeared for 1000ms. Then, the mask disappeared, and participants were presented with two different frame options. One option contained the soccer ball, and one did not. On each trial, the two probe frames were taken from either midway through the first half of the event (frame 15), or midway through the second half of the event (frame 45). Thus, the only difference between the two options was the presence or absence of the soccer ball. Participants gave a two-alternative forced-choice (2AFC) response in choosing which frame they remembered seeing by using the arrow keys on their keyboard.

Participants completed 32 trials total; each video was presented twice, such that participants' memory could be independently tested for the two halves of the event. This also ensured that every aspect of the experiment was counterbalanced. The order of the videos was randomized for each participant. Trials with a response time below 200ms were excluded for being too fast, as per our pre-registered analysis plans. In each experiment, we excluded subjects who did not submit a complete dataset.

These timing parameters, exclusion criteria, randomization, etc. were consistent across all experiments; each experiment used these same methods. In other words, the experiments differ in their stimuli (either in the videos or in the probe frames), but not in their design, response method, or instructions.

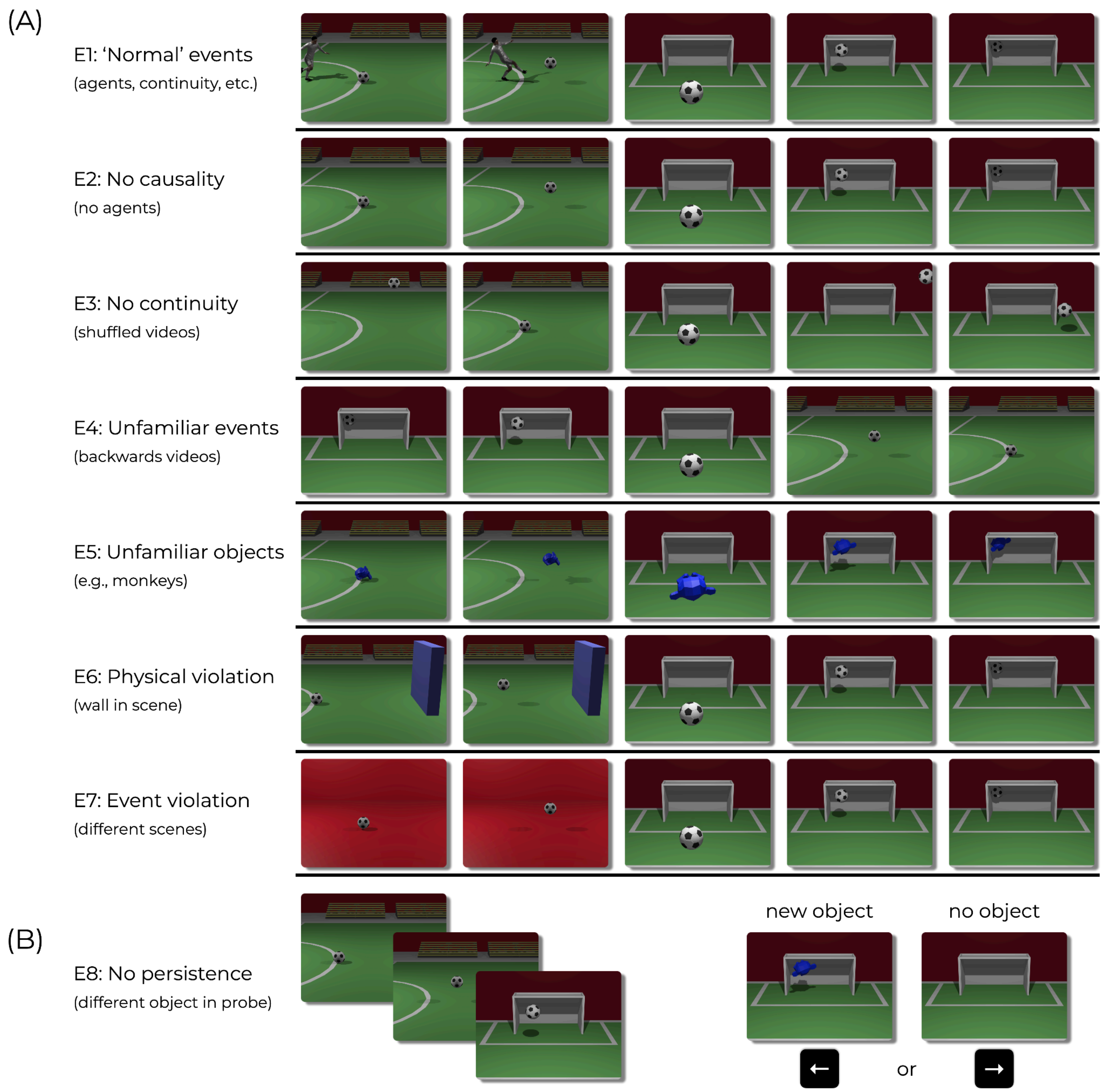

Fig 2. In 8 experiments, we systematically manipulated certain parts of the event and asked whether event completion would still arise. (A) Overview of how each experiment differed; Experiments 1–7 presented videos that removed various features (e.g., causality, continuity, etc). (B) In Experiment 8, we violated persistence by (on some trials) presenting probe frames that contained different objects from the ones in the video.

Results

We predicted that, after seeing the soccer ball in one part of the animation, participants would fill-in its presence in the other part of the animation. Validating this prediction requires observing two key patterns beyond just a high false positive rate on present-absent and absent-present videos. First, we must observe that such filling-in effects are not merely the result of a bias towards responding that an object was present; to show this is not the case, we should observe high accuracy (i.e., low filling-in) on absent-absent videos. Second, we must observe that these effects are not explained by inattention in general; to show this is not the case, we should observe high accuracy (i.e., low inattention) on present-present videos (along with the high accuracy on absent-absent videos, as before).

First, we performed a 2-factor ANOVA asking how accuracy varies by 'pure events' (i.e., present-present or absent-absent, where the ball is either present or absent in both halves) vs. 'mixed events' (i.e., present-absent or absent-present, where the ball's presence is mixed across the halves) and agent type (kicking agent present in first half, versus saving agent present in second half). We observed a significant effect of event purity, suggesting that pure events differ in accuracy from mixed events ($F(1, 39) = 23.68$, $p < .001$; mean pure event accuracy = 95.8% vs. 85.2% for impure events). This provides evidence against the object-presence bias and inattention hypotheses, as accuracy on absent-absent and present-present trials is near ceiling.

We also observed a significant effect of agent type ($F(1, 39) = 4.23$, $p = 0.046$; mean kicking agent accuracy = 92.0% vs. 88.9% for goalie agents). However, subsequent experiments suggest that agent presence does not account for this distortion alone; rather, agent presence may just affect the strength of the distortion. This modulation may occur for a few different reasons even beyond the fact that agents provide a causal start and end to these events. Perhaps the presence of an agent helps participants 'tag' the ball as being present or absent in each half of the event; or perhaps the presence of an agent merely enhances attention to the relevant half of the event. However, it is unclear how to disentangle these possibilities, as they may cash out in different directions here. For example, on the 'tagging' hypothesis, one may expect to observe *higher* false positive rates with agents than without agents, given that agents typically perform actions *on* objects (i.e., if you see someone kick, you may expect they were kicking an object). But this runs contrary to what we observe when we remove agents in later experiments. Alternatively, on the hypothesis that agents enhance attention, one may expect to observe *lower* false positive rates; but this would be due to a downstream consequence of agent presence (i.e., enhanced attention), rather than a direct consequence of agent presence itself. Thus, it seems safest to interpret the effect of agents by observing what happens when we remove agents in our subsequent experiments.

Next, we compared filling-in effects for the 'impure events' when subjects were probed on the 'absent' parts of the video. In other words, when probed on the 'absent' part of an absent-present or present-absent event, are false positive rates substantially higher than those of the same part of absent-absent videos? Our results show that false positive rates were indeed higher on these impure events; when probed on the first half of absent-present videos, subjects were significantly less accurate than when they were probed on the first half of absent-absent videos (mean difference = 12.5%, $t(39) = 3.73$ in paired t-test on subject-level means, $p < .001$, $d = 0.59$, 95% CI = [5.72%, 19.27%]). The converse was also true; false positive rates (i.e., rate of filling-in) were significantly higher when subjects were probed on the second half of present-absent videos than when they were probed on the second half of absent-absent videos (mean difference = 18.1%, $t(39) = 4.42$, $p < .001$, $d = 0.70$, 95% CI = [9.83%, 26.42%]; Figure 3A).

This first experiment suggests that: a) participants fill-in the presence of a ball in one part of a video after seeing it in another part of a video, and b) these results are not merely due to an object-presence bias or inattention more broadly. With this paradigm in hand, we can now systematically remove various cues and ask whether the distortion survives.

Experiment 2: Distortions without causality

Although Experiment 1 revealed a memory distortion, it is unclear what caused the distortion. The videos contain cues to many different features, such that it is difficult to pinpoint a specific feature that underlies event completion. For example, though event purity seems to be the main statistical factor underlying these distortions, perhaps the presence of causal agents modulated this effect (Kominksy et al., 2021). After all, the mind quickly and spontaneously encodes the roles of causal agents in an event, perhaps in a way that influences further processing (Hafri et al., 2013; Hafri et al., 2018). Furthermore, agenthood affects how people understand when events start and end (Mathis & Papafragou, 2022). And more generally, the presence of *causal implication* is said to be an important factor for event completion (Strickland & Keil, 2011; Kominsky et al., 2021). Thus, the presence of causality (or causal agents) may impact event-based distortions in a variety of ways. In Experiment 2, we presented subjects with the same task as in Experiment 1, but now removed the agents from the videos. Thus, these videos did not have causal starts and ends. Would the same filling-in effects arise?

Method

Participants

40 new participants were recruited.

Stimuli and Procedure

This experiment contained only 8 videos. The videos were created by matching all combinations of: 4 object presence (present-present, absent-absent, absent-present, and present-absent) × 2 shot type (low shot vs. power shot). Comparatively, Experiment 1 contained 16 videos, because there were also 2 kinds of agents (kicking agent or goalie agent), allowing for twice as many combinations.

The experimental design here was exactly the same as that of Experiment 1. On each trial, participants watched a 2-second video. After the video ended, a box-scrambled mask appeared for 1000ms. Then, the mask disappeared and participants were presented with a two-alternative forced-choice task. On each trial, the two options were taken from the same temporal point of the video (either frame 15 or frame 45); the only difference between the two options is that one contained a ball, and one did not. Given that there were 8 videos, and participants saw each video twice (such that they can be probed on both the first half and the second half independently), there were 16 total trials in this experiment. Thus, everything about the design of this task was the same as in Experiment 1 — including counterbalancing, randomization, and experimental instructions. The only difference is in the stimuli; whereas the videos in Experiment 1 contained causal agents, these videos contained no agents at all.

Of course, sometimes we infer that an agent was present even if we do not see one. For example, suppose the first frame of the video contained the ball on the left-most side of the screen, already flying through the air. It would be reasonable to think that an agent off-screen kicked the ball, and to thus assume that we are just seeing the ball's resultant motion. We designed our stimuli such that this would not be a possibility. The first frame in these animations depicted the ball sitting still in the center of the frame — just like the animations in Experiment 1. Thus, the events in this experiment contained no agents, and also contained no possible implications of inferred agents.

Results

As before, we observed a significant effect of event purity ($F(1, 39) = 44.38$, $p < .001$; mean pure event accuracy = 97.2% vs. 79.1% for impure events). Furthermore, the critical probes (i.e., probing on the absent part of impure events) revealed similar false positive rates to Experiment 1. Participants consistently filled in a ball when probed on the first half of absent-present videos (and this false positive rate was higher here than for absent-absent videos; mean difference = 22.5%, $t(39) = 3.80$, $p < .001$, $d = 0.60$, 95% CI = [10.52%, 34.48%]). This also held true for the second half of present-absent videos (mean difference = 35.0%, $t(39) = 5.60$, $p < .001$, $d = 0.88$, 95% CI = [22.35%, 47.65%]; Figure 3B).

Thus, event completion occurs even in the absence of causality (i.e., without causal agents). Even though agent type had a significant effect in Experiment 1, it seems that causality alone cannot account for this effect. This rules out one explanation for such distortions (suggested by prior work, such as Kominsky et al., 2021): Without agents, the memory distortion still occurs.

Experiment 3: Distortions without continuity

We see that participants still fill-in the presence of an object in the absence of causal agents. However, removing the agents in our videos manipulated only the surrounding *event*, and not a feature of the *object* itself (i.e., the object that is a constituent of the event and the subject of the probe). Might this distortion survive changes to the object in question?

Spatiotemporal continuity is perhaps the most salient feature the mind uses for indexing and tracking objects. Indeed, one reasonable way to create a coherent memory or representation of two discrete time-points, *t1* and *t2*, is to ask whether an object was spatiotemporally continuous across those two time points (Scholl, 2007). Such continuity is so powerful that both infants (Spelke et al., 1995; Xu & Carey, 1996; Kibbe & Leslie, 2019) and adults (Li et al., 2023) fail to notice changes to an object when it moves continuously over time.

Some memory distortions have been shown to require continuity. For example, representational momentum disappears in the absence of continuity (Experiment 2 of Freyd & Finke, 1984); conversely, faster and more continuous displays create larger momentum effects (Finke & Freyd, 1985; for additional discussion, see Hubbard, 1995). Similar ideas have been proposed for event completion (Kominsky et al., 2021) and event representation more broadly (Altmann & Ekves, 2019). Thus, perhaps spatiotemporal continuity underwrites our observed distortion. Here, we presented subjects with videos in which the ball moved along a discontinuous path and asked whether the same event completion effects would arise.

Method

Participants

40 new participants were recruited.

Stimuli and Procedure

This experiment contained 16 total videos. We reached this number via the following combinations: 4 object presence types × 2 shot types × 2 continuity types (discontinuous vs. continuous). Note, then, that this experiment contained all the videos from Experiment 2 (4 object presence types × 2 shot types, all continuous) with the addition of discontinuous videos. In the discontinuous videos, the ball moved in one path for a few frames, before teleporting to another location and taking a new path, before teleporting and moving again. Thus, its motion was discontinuous in that from one frame to the next, it moved in a choppy fashion.

As before, the 16 total videos we created resulted in 32 total trials (as each video is presented twice, once when probed on the first half and once when probed on the second half). The task that participants performed was the same as in previous experiments.

Results

We observed a significant effect of event purity ($F(1, 39) = 27.59$, $p < .001$; mean pure event accuracy = 92.6% vs.79.8% for impure events) but not continuity ($F(1, 39) = 0.09$, $p = 0.77$; mean continuous event accuracy = 86.5% vs. 85.9% for discontinuous events). Furthermore, there was no interaction between the two factors ($F(1,39) = 0.46$, $p = 0.50$). In other words, there seems to be no effect of continuity on this memory distortion. We further observed this through the high rates of filling-in for discontinuous videos; both absent-present videos (when probed on the 'absent' part, relative to absent-absent when probed on the first half; mean difference = 26.3%, $t(39) = 4.07$, $p < .001$, $d = 0.64$, 95% CI = [13.20%, 39.30%]) and present-absent videos (when probed on the 'absent' part, relative to absent-absent when probed on the second half; mean difference = 23.8%, $t(39) = 3.68$, $p < .001$, $d = 0.58$, 95% CI = [10.70%, 36.80%]; Figure 3B) showed a considerable filling-in effect. Thus, spatiotemporal continuity cannot explain this effect.

Experiment 4: Distortions in unfamiliar events

In Experiment 4, we attempted to rule out an event-familiarity-based explanation for this effect. In other words, perhaps people fill-in objects only for forward-playing events unfolding over time in familiar ways — and thus would not fill-in objects for backward-playing events (that unfold over time in unfamiliar ways). Previous work shows that event completion survives controls for familiarity insofar as it arises in both naturalistic stimuli and synthetic stimuli (Kominsky et al., 2021). Related phenomena such as representational momentum have been shown to survive in backward-playing events (Hafri et al., 2022). But it is unclear whether event completion survives this control for familiarity too. To test this, we presented participants with videos that played in reverse. This manipulation allows us to not only probe the power of familiarity but also disrupt causality further (as backward-playing events are necessarily non-causal).

Method

40 new participants were recruited.

Stimuli and Procedure

Experiment 4 contained 16 total videos: 4 object presence types × 2 shot types × 2 video directions (forward vs. backward). We asked whether a filling-in effect would still arise for backward-playing videos (i.e., to a similar extent as in forward-playing videos). Participants performed the same task as in previous experiments.

Results

We observed memory distortions regardless of video direction, suggesting that our effect survives for unfamiliar events. Video direction had no effect on accuracy ($F(1, 39) = 0.62$, $p = 0.44$; mean accuracy for normal videos = 87.7% vs. 88.6% for reversed videos); event purity was significant, as it was in other experiments ($F(1, 39) = 37.62$, $p < .001$; mean accuracy for pure events = 95.0% vs. 81.4% for impure events); and there was no significant interaction between the two ($F(1, 39) = 1.86$, $p = 0.18$). We observed the requisite patterns in the 'absent' parts of the backward-playing videos (absent-present vs. absent-absent, mean difference = 25.0%, $t(39) = 4.65$, $p < .001$, $d = 0.74$, 95% CI = [14.14%, 35.86%], present-absent vs. absent-absent, mean difference = 23.8%, $t(39) = 4.43$, $p < .001$, $d = 0.70$, 95% CI = [12.89%, 34.61%]; Figure 3B). Thus, it seems that the mind transforms incoherent memories into coherent ones even when events unfold in unfamiliar directions.

Experiment 5: Distortions with unfamiliar objects

Experiment 4 demonstrated that event completion occurs for events that unfold in unfamiliar directions. However, one further way to manipulate 'familiarity' in this case is to render events that contain unfamiliar objects. In other words, perhaps people fill-in a soccer ball in our previous experiments only because soccer balls co-occur with soccer fields (i.e., perhaps people think that most soccer fields contain soccer balls). If this was the case, then people would not fill-in an object that rarely appears on a soccer field. Would event completion survive this additional control for familiarity? To address this question, we rendered videos containing a surprising and unfamiliar object — specifically, a monkey head — instead of a soccer ball, and asked whether the same distortion would occur.

Method

Participants

40 new participants were recruited.

Stimuli and Procedure

We rendered 16 total videos by creating all combinations of: 4 object presence types × 2 shot types × 2 objects (soccer ball vs. monkey head). The monkey head was a solid blue color, such that it was especially salient and unexpected. Importantly, the soccer ball and monkey head followed the exact same trajectory; thus, any observed differences between the two (or lack thereof) would be due to the difference in the appearance of the objects. We asked whether filling-in would occur for monkey videos (to a similar extent as it did for soccer ball videos).

Results

We observed no difference across the two object types ($F(1, 39) = 0.04$, $p = 0.85$, mean accuracy for monkey videos = 88.9% vs. 89.2% for soccer videos); we observed the same strong effect of event purity ($F(1, 39) = 42.2$, $p < .001$, mean accuracy for pure events = 96.7% vs. 81.4% for impure events); and we did not observe any interaction between the two ($F(1, 39) = 0.18$, $p = 0.67$). Participants filled-in the presence of a monkey in the relevant parts of the videos, even though a monkey does not match the expected scene statistics or object template for a soccer field (absent-present vs. absent-absent, mean difference = 32.5%, $t(39) = 5.12$, $p < .001$, $d = 0.81$, 95% CI = [19.67%, 45.33%], present-absent vs. absent-absent, mean difference = 21.3%, $t(39) = 4.52$, $p < .001$, $d = 0.72$, 95% CI = [11.75%, 30.75%]; Figure 3B). Thus, the distortion survived disruptions of familiarity to not only the event (as in Experiment 4), but also the object itself (as in this experiment).

Experiment 6: Distortions without physical coherence

One possible explanation for the previously-observed effects is physical coherence, which underwrites various object- and event-based representations (Spelke et al., 1992; Scholl, 2007). Physical coherence is a catch-all for a variety of spatiotemporal features, including solidity and continuity. For example, suppose you see a violation of physical coherence where a ball passes through a solid wall. This violation could arise due to either a violation of solidity (allowing the ball to pass through the wall) or a violation of continuity (allowing the ball to 'jump' from one side of the wall to the other without passing through the wall). Thus, physical coherence may be a rich and strong explanation for these distortions, as it integrates multiple different potential cues. Might the effect exist even if filling-in required assuming a violation of physical coherence? We tested this directly by rendering videos that contained a large barrier in front of the ball; for the ball to end up in the goal in these events, a violation of physical coherence must have occurred. Thus, if physical coherence explains these effects, then adding a wall should remove the effect.

Method

Participants

40 new participants were recruited. 1 participant did not complete the task, so we received full data from 39 participants.

Stimuli and Procedure

We rendered 16 total videos: 4 ball presence conditions × 2 shot types × 2 physical coherence conditions (wall vs. no wall). The wall was placed directly in front of the ball in the first half of the scene, making it such that there was no way for the ball to continue its trajectory towards the goal. The wall was also very large, such that it would be easily noticed by participants. Using the same experimental designs as before, we asked whether filling-in effects would decrease on videos that included a wall.

Results

Participants filled-in the presence of a ball even when its presence implied a physical violation. There was no significant effect of physical coherence on accuracy ($F(1, 38) = 0.22$, $p = 0.64$; mean accuracy on videos with wall = 87.0% vs. 87.8% on physically coherent videos with no wall; as before, event purity was significant ($F(1, 38) = 32.71$, $p < .001$; mean accuracy on pure events = 94.7% vs. 80.1% on impure events); and there was no significant interaction between the two ($F(1, 38) = 1.03$, $p = 0.32$). We further confirmed this by looking at trials where the wall was present: On absent-present trials, participants filled in the ball in the absent part significantly more than on absent-absent trials (mean difference = 28.2%, $t(38) = 4.91$, $p < .001$, $d = 0.79$, 95% CI = [16.57%, 39.84%]); and this was also true of present-absent trials (mean difference = 19.2%, $t(38) = 3.07$, $p < .01$, $d = 0.49$, 95% CI = [6.56%, 31.90%]; Figure 3B).

A priori, one may expect physical coherence to be the strongest trigger for event completion, given that physical coherence encompasses multiple important spatiotemporal cues together. However, we observe that violating physical coherence was not enough to abolish event completion.

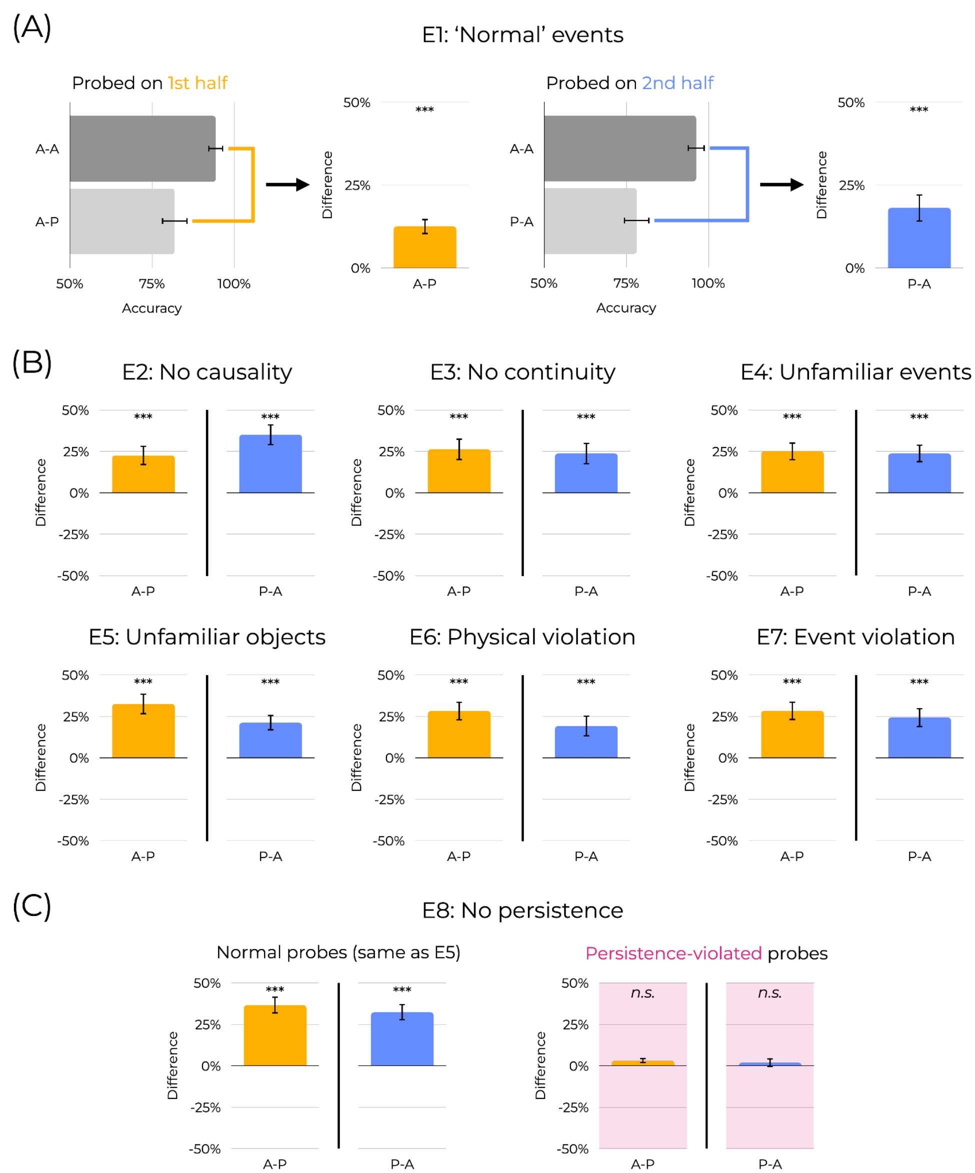

Fig 3. Results of all experiments. (A) In Experiment 1, we observed event completion for normal events; participants filled-in the presence of a ball when it was not there. We compare accuracy for absent-present events (A-P) when probed on the first half (i.e., the absent part) to accuracy for absent-absent events (A-A) when probed on the first half. We computed a difference score for each participant, then averaged the scores across participants. We did the same for present-absent events (P-A) probed on the second half vs. absent-absent events (A-A) probed on the second half. In subsequent panels, only these difference scores are depicted. (B) In Experiments 2-7, we found the same memory distortion regardless of the manipulations we performed. The graphs depict the difference scores for trials with the relevant stimuli manipulation (e.g., Experiment 5 contained both soccer ball and monkey head videos, and the graph depicts difference scores for the monkey head videos). (C) In Experiment 8, we manipulated object persistence by replacing the lure probes on half of the trials. On the half of trials that used the same memory probes as in previous experiments, we found the same filling-in effects as before (left). However, on the half of trials when the object in the memory probe differed from the object in the animation, we observed no event completion effects (right). In the absence of persistence, event completion disappeared. Error bars depict SEM. Significance stars are from one-sample *t*-tests on this difference score (e.g., as depicted in (A)). All data and analyses are available at https://osf.io/pfxud/.

Experiment 7: Distortions without event coherence

Perhaps the strongest assumption for event-based memory distortions is that they require coherent events. In other words, if two events are notably different, one would not expect a memory distortion in one event to bleed into another event and create a corresponding distortion there. Indeed, 'event boundaries' such as doorways (a boundary between two rooms) cause forgetting (Radvansky & Copeland, 2006). Even the mere *anticipation* of an event boundary may trigger active forgetting (Wang et al., 2023). Thus, one might expect that event completion should disappear for events that consist of visually different parts or 'rooms.' Here, we rendered new animations in which the two halves of the event took place in very different scenes; one half took place on a soccer field, and one half took place in a bright red room. Would this disruption of event coherence cause a corresponding disruption in event completion effects?

Method

Participants

40 new participants were recruited. 3 participants did not complete the task, meaning that we analyzed data from 37 participants.

Stimuli and Procedure

To test disruptions of event coherence, we rendered animations where the two halves of the event differed substantially. Sometimes, one half of the event took place on a soccer field (i.e., the same sort of event as in all previous experiments); sometimes, one half of the event took place in a bright red room (which was very visually distinct from a soccer field). To ensure our stimuli were counterbalanced, we generated animations in all 4 possible combinations of these scenes: soccer-soccer (i.e., both halves take place on a soccer field, as in previous experiments), red-red (i.e., both halves take place in a red room), soccer-red (i.e., the first half talke place on a soccer field, and the second half takes place in a red room), and red-soccer (i.e., the first half takes place in a red room, and the second half takes place on a soccer field). Thus, we rendered 32 videos: 4 ball presence conditions × 2 shot types × 4 event coherence (soccer-soccer, red-red, soccer-red, and red-soccer). As before, 32 videos resulted in 64 trials (as each video appeared twice), and participants completed the same task as in previous experiments.

Results

Participants completed events even when the events themselves were not coherent. In other words, if a soccer ball appeared in one half of the animation, participants filled-in its presence in the other half of the animation even when the two halves themselves consisted of visually different events and scenes. This is first evidenced by an ANOVA modeling accuracy by event purity, 'event match' (whether the two halves of the event are the same, i.e., soccer-soccer and red-red, or whether the two halves of the event are different, i.e., soccer-red and red-soccer), and their interaction. As in other experiments, the role of event purity was significant ($F(1, 36) = 41.75$, $p < .001$; mean pure event accuracy = 96.3% vs. 81.3% for impure events). However, the role of event coherence (i.e., event match) was not significant ($F(1, 36) = 1.41$, $p = 0.24$; mean event-match accuracy = 88.2% vs. 89.4% for non-event-match), nor was the interaction between event purity and event coherence ($F(1, 36) = 0.72$, $p = 0.40$). In other words, we observed filling-in effects for incoherent events (absent-present vs. absent-absent when probed on the first half mean difference = 28.4%, $t(36) = 5.09$, $p < .001$, $d = 0.84$, 95% CI = [17.06%, 39.69%]; present-absent vs. absent-absent when probed on the second half mean difference = 24.3%, $t(36) = 4.22$, $p < .001$, $d = 0.69$, 95% CI = [12.62%, 36.03%]; Figure 3B). Thus, event completion persists even across visually different events.

Experiment 8: No distortions without persistence

We have demonstrated in our first 7 experiments that several candidate explanations fail to account for event completion on their own. However, to provide evidence for our positive proposal — that object persistence underwrites event completion — we must show that abolishing object persistence abolishes event completion. Is this the case? In other words, does event completion disappear in the absence of object persistence?

Method

Participants

41 new participants were tested. (We intended to recruit 40 participants, and pre-registered that number, but 41 participants were tested due to an error with Prolific.)

Stimuli and Procedure

This experiment contained the same set of videos as Experiment 5 (monkey vs. soccer ball). Thus, it contained 16 videos (4 object presence types × 2 shot types × 2 objects). Our key manipulation of object persistence came in the memory probes. After seeing a video, participants were faced with two options for the frame they saw, as in other experiments. One option was correct. Whereas in previous experiments the difference between the correct and incorrect frame was the presence or absence of an object, here our 'lure' probes varied across trials in ways that abolished object persistence.

There were 2 types of lure probes — “object-congruent” lures, in which the incorrect frame contained the same object as seen in the video, and “replacement” lures, in which the incorrect frame contained a different object from the one in the video. For example, suppose a participant was shown a soccer ball absent-present video, and was then probed on the first half of the video. Experiments 1–7 would contain two frame options for this probe: a frame with no object (the correct answer), and a frame with a soccer ball (the incorrect answer via a lure that would cause filling-in for the same, persisting object from the video). The frame with the soccer ball is “object-congruent,” as it contains the same object seen in the video itself. In other words, all the lure frames used in Experiments 1–7 were object-congruent. However, in this experiment we added another kind of lure: “replacement.” Using the previous example of a soccer ball absent-present video, the lure frame here would contain a monkey — a different object from the one seen in the video. Thus, the replacement lures violate object persistence, as filling-in the presence of an object would mean the soccer ball transformed into a monkey. This would imply pointing to (and creating) a different object-file, thus violating object persistence.

Note that this manipulation applies *only* to the probe frames; the events and animations themselves are the exact same as in Experiment 5. Given this manipulation, our experiment contained 64 trials total: 16 videos × 2 probe frames (probed on the first half or probed on the second half) × 2 lure types (object-congruent or replacement).

Results

As in each of our other experiments, accuracy significantly differed with event purity ($F(1, 40) = 57.48$, $p < .001$; mean pure event accuracy = 98.0% vs. 86.7% in impure events). However, lure type (object-congruent vs. replacement) also modulated this effect ($F(1, 40) = 53.77$, $p < .001$; mean object-congruent accuracy = 87.7%, mean replacement accuracy = 97.1%), and had a significant interaction with event purity ($F(1, 40) = 35.87$, $p < .001$). This is the first manipulation that has successfully disrupted event completion. In other words, none of our other manipulations affected the magnitude of filling-in — but abolishing object persistence did.

Subsequent *t*-tests revealed that abolishing object persistence removed the effect entirely. In object-congruent lure trials — i.e., where the lure matches the object seen in the video, as in our other experiments — participants had high false positive rates, meaning they filled in the presence of the ball (absent-present tested on the first half vs. absent-absent trials, mean difference = 36.6%, $t(40) = 7.18$, $p < .001$, $d = 1.12$, 95% CI = [26.28%, 46.89%]; present-absent trials tested on the second half vs. absent-absent trials, mean difference = 32.3%, $t(40) = 6.42$, $p < .001$, $d = 1.00$, 95% CI = [22.14%, 42.49%]). This is in-line with our previous results (indeed, the object-congruent lure trials are a direct replication of Experiment 5). However, in replacement lure trials — where the lure differed from the object seen in the video, thus violating object persistence — there was no filling-in effect, even for impure events. In other words, participants no longer filled-in the presence of an object after seeing it in one part of an event (absent-present first half vs. absent-absent, mean difference = 3.0%, $t(40) = 1.95$, $p = 0.06$, $d = 0.31$, 95% CI = [-0.11%, 6.20%]; present-absent second half vs. absent-absent, mean difference = 1.8%, $t(40) = 0.68$, $p = 0.50$, $d = 0.11$, 95% CI = [-3.58%, 7.24%]; Figure 3C). Thus, it seems that object persistence explains event completion.

Initially, one may try to explain away the effect here by claiming that subjects see the replacement lures as constitutive of a separate event from the one shown in the animation. In other words, perhaps this experiment actually manipulates event continuity. However, we feel this is not a viable explanation for 3 reasons: 1) the events presented in this experiment are the exact same as the ones presented in Experiment 5 (i.e., the only difference is in the probes, and there is no difference in the events themselves), 2) Experiment 3 shows that the effect survives in the absence object continuity, and 3) Experiment 7 demonstrates that the effect persists even when the two halves of the event differ. In each of these cases, event completion still occurred. The last of these points is especially important: Experiment 7 demonstrates that event completion occurs even for events that are in fact separate. So, to say that a violation of persistence leads the events to be perceived as separate would require evidence of effects similar to those in Experiment 7. But this is precisely the opposite of what we observe here in Experiment 8. Thus, we think these results point to the power of object persistence itself.

The effect of persistence is especially striking given that no other manipulation successfully diminished event completion effects. Prior to this experiment, one may have worried that the paradigm was biasing subjects to complete events; in other words, perhaps *no* manipulation would disrupt event completion in this paradigm. However, we show that a violation of persistence removed this distortion. This both provides evidence for our positive proposal and testifies to the validity of our paradigm more broadly.

Mega–analysis of Experiments 1–7

In Experiments 1–7, we found that a variety of cues were unable to explain event completion. Each experiment revealed the same type of effect — participants filled-in the presence of an object even when certain cues are disrupted. Thus, we can aggregate data across these 7 experiments (which were completed by 276 subjects total) to answer fine-grained questions that each individual experiment was not powered to answer.[1] For example, might these effects arise as a byproduct of learning over the course of an experiment? Might we observe stronger distortions on the first half of an event than the second half (i.e., effects of order within an event)? Might confusion more generally underwrite our results (in ways beyond the absent-absent baseline we establish in each experiment)? We approach these questions by

[1] These analyses were conducted after we collected all the data for the project; so, this mega-analysis is not pre-registered. However, note that each experiment's design, analysis, sample size, etc. was pre-registered.

conducting a mega-analysis of our 7 experiments that show consistent distortions (i.e., excluding Experiment 8, where we disrupt the distortion).

Learning effects (across trials)?

One potential worry in our experiments is that the memory distortions are caused by proactive interference from previous trials. In other words, perhaps participants fill-in the object because they saw it in a previous video. Under this hypothesis, though, we should observe no filling-in effects on the first trial of our experiment, as no interference is possible then.

However, when aggregating data across Experiments 1–7, we find evidence for a distortion from the start of the experiment. On the very first trial of the experiment, participants *still* show filling-in effects. There was a significant difference between accuracy for 'pure' events (i.e., present-present and absent-absent; 90.6%) and accuracy for 'impure' events (i.e., present-absent and absent-absent; 59.1%) even on the first trial of the experiment ($t(220.34) = 6.45$, $p < .001$, $d = 0.78$, 95% CI = [21.89%, 41.16%]).[2,3,4]

This learning cannot explain our effects if one posits it in the opposite direction, either: Event completion effects arise even on the *last* trial. Here, accuracy on pure event trials was 97.3%, compared to 88.5% on impure event trials ($t(186.91) = 2.82$, $p < .01$, $d = 0.35$, 95% CI = [2.64%, 14.96%]).[5] This effect is numerically smaller than what we observed on the first trial; but this is perhaps to be expected, as participants should become more accurate over time just from

[2] This analysis actually undersells the strength of this effect. We are primarily interested in how often participants fill-in the object for impure events when they are probed on the 'absent' part of the event. We know that accuracy when probed on the 'present' part of impure events is comparatively higher, as participants rarely deleted the object. However, this analysis collapses across these two types of probe frames. If we limit the first-trial impure events here to those where participants are probed on the absent half of the event — i.e., the relevant half for event completion — then we observe an even larger effect. The accuracy for impure events in this case is 51.8% ($t(165.88) = 7.20$, $p < .001$, $d = 0.97$, 95% CI = [28.19%, 49.47%]) — i.e., participants completed events nearly 50% of the time. Thus, the difference between the pure and impure events here is even larger than it may seem.

[3] Another potential question regarding this analysis concerns the unpaired nature of this test. This analysis is conducted on the very first trial each participant sees; so, each participant contributes only a single value. This could be an issue if, for example, the impure events simply catch participants by surprise, leading to higher false positives on the first trial. To account for this explanation, we conducted a similar test with one key change: Instead of comparing accuracy for pure events vs. impure events on the first trial for each participant, we compared accuracy for pure events vs. impure events on the first trial *of each kind* that each participant completed. This allows us to not only conduct a paired test (as each participant now contributes one value for pure events and one value for impure events) but also address the surprise-based explanation above. With this new test, we find the same pattern of results: Mean accuracy on the first impure event trial each subject saw was 67.8%, compared to 93.5% on the first pure event trial they saw ($t(275) = 8.20$, $p < .001$, $d = 0.49$, 95% CI = [19.55%, 31.90%]).

[4] We also conducted this — and other tests — as an ANOVA with a between-subjects factor of experiment number, just in case there was any significant variation across experiments. However, we found no significant effect of experiment number, and all of our key effects arose to the same extent. This is perhaps to be expected given the fact that our effect was highly consistent across each experiment. Thus, for simplicity, we report only *t*-tests.

[5] As before, converting this to a paired test on the last trial of each kind reveals the same pattern: Mean accuracy on the last impure event trial for each participant was 88.4%, compared to 96.7% on pure events ($t(275) = 3.89$, $p < .001$, $d = 0.23$, 95% CI = [4.10%, 12.57%]).

experience with the task. Still, given that participants complete events on both the first and the last trial of our experiments, it seems that learning or interference alone cannot be the main driver for the observed event completion effects.

Order effects (within events)?

Although learning effects do not arise across trials, it is possible that order effects exist within a single trial. In other words, are participants more likely to fill-in the object for absent-present events than for present-absent events (or vice versa)?

Many reasonable hypotheses may lead to either prediction. For example, perhaps memory is better for the second part of an event simply because the information from the second part of an event is more recent (and thus more readily available and accurate) than the information from the first part of an event. On the other hand, perhaps memory for the first part of an event is stronger because participants pay more attention to the 'start' of each event. More generally, a result in either direction may be taken as evidence for or against event completion as backward inference (as opposed to predictive perception; Papenmeier et al., 2019).

Many of our experiments contain built-in controls for these possibilities. Most notably, Experiment 4 tested event completion effects for forward-playing vs. backward-playing videos (within-subject). If event order substantially modulated event completion, then this experiment seems to be a direct way to test such an effect. However, we found no effect of video direction here.

Still, to test whether order effects within an event might arise, we compared absent-present events (probed on the first half) to present-absent events (probed on the second half) across our experiments. We found no evidence a difference in these conditions: Accuracy on absent-present events (probed on the absent part) was 70.4%, while mean accuracy on present-absent events (probed on the absent part) was 71.9% ($t(275) = 0.78$, $p = 0.43$, $d = 0.05$, 95% CI = [-2.31%, 5.36%]). Thus, while it is possible that multiple different explanations are working in opposite directions here, it seems the simplest interpretation is just that event completion can happen *anywhere* in an event (as long as the object persistence is not violated).

Confusion?

One additional concern regarding our results is that participants are simply confused by impure events. When doing our experiments, participants must remember not only whether or not an object was present in an event, but also remember *when* in the event it was present (or absent). Thus, perhaps participants know that the object was absent in one half and present in the other, but merely lose track of which half was which at test, leading to inaccuracies on impure events.

This hypothesis gives rise to a key empirical prediction: If subjects are confused about when an object was present or absent, then they should be just as likely to fill-in an object in the absent half as they are to *delete* an object in the present half. In other words, accuracy on absent-present events should be equal regardless of whether subjects are probed on the absent half or the present half (and likewise for present-absent events). However, we observe an asymmetry here. Mean accuracy on absent-present events when probed on the absent half was 70.4%, compared to 90.5% in those same events when probed on the present half ($t(275) = 8.45$, $p < .001$, $d = 0.51$, 95% CI = [15.42%, 24.80%]); similarly, average accuracy on present-absent events when probed on the absent half was 71.9%, compared to 91.9% in those same events when probed on the present half ($t(275) = 10.08$, $p < .001$, $d = 0.61$, 95% CI = [16.10%, 23.91%]). Thus, confusion cannot explain these results.

Altogether, this mega-analysis reveals that our observed event completion effects are not due to interference across trials, event order within trials, or confusion in impure events. Nor was it due to an object-presence bias or general inattention (as demonstrated in each experiment's individual results). Rather, the event completion effects we found seem to be indicative of a legitimate memory distortion.

General discussion

What causes memory distortions like event completion? Here, we found a filling-in effect where people misremembered seeing a ball when it was in fact not there if the ball was shown in another part of the event (E1). Using this initial distortion, we programmatically tested a set of possible explanations for this effect, including representations of causality (E2), continuity (E3), event familiarity (E4), object familiarity (E5), physical coherence (E6), and event coherence (E7). We found the effect survived each of these manipulations. However, abolishing object persistence removed the effect (E8). Thus, we suggest object persistence is the simplest and most fundamental explanation for event completion.

Our results add to a broad tradition of research on object and event expectations in both infants and animals. Permanence is among the earliest-developing expectations about objects; infants as young as 3.5 months old reliably expect objects to persist over time (Baillargeon et al., 1985; Baillargeon, 1987). Furthermore, results in controlled rearing of chicks present similarly strong evidence regarding the innateness of object permanence, with some work showing that such expectations cannot be overwritten (Wood et al., 2024; Prasad et al., 2019). In other words, research from both infants and animals suggests that object permanence may be an evolutionarily ancient inductive bias for visual perception. Although each set of results here may conceive of permanence or persistence in a way different from how we do here (see below for more discussion on these differences), the key ideas remain connected: We hold early and strong expectations that objects will continue to exist over time. This expectation (and other kinds of object expectations, such as continuity) may account for a variety of “errors” or “shortcuts” that even adults employ (e.g., Strickland and Scholl, 2015; Li et al., 2023). Here, we show that this expectation may be so strong that it distorts our memories of the presence of objects.

More broadly, these results shed light on how we may represent objects and events in visual working memory. At first, our proposal that object persistence underlies memory distortions may appear reductionist. However, if we conceive of these kinds of memory distortions as ones that require an event to contain a persistent object-file, then a persistence-based explanation may be the most intuitive. An expansive research tradition explores what kinds of changes impair our representations of visual objecthood. One key finding of this literature is that multiple object tracking survives natural occlusion, but does not survive other forms of appearing and disappearing (e.g., implosion and explosion; Scholl & Pylyshyn, 1999). In other words, object-file representations survive occlusion, allowing us to continue tracking objects when we do not see them. We suggest that such residual object-file representations may persist in the absence of the object itself, leading to memory distortions such as event completion.

In this line of thinking, one explanation for our effects is that participants falsely remember having seen an object after it disappeared because their object-file had not yet been destroyed. Only changing the object itself destroyed the object-file in our experiments. Thus, in much the same way that physical intuitions may actively distort our memories for how scenes will play out (Hafri et al., 2022), so too do persistence expectations actively transform our memories of incoherent scenes into coherent ones. Future work may further examine how — and when — such object-files ‘break’. For example, is a persistence violation in a surface-level feature — i.e., if a lure probe depicts a red soccer ball, while the video shows a white soccer ball — enough to destroy this file? Would other kinds of object changes — such as topological transformations, which have been shown to impair multiple object tracking (Zhou et al., 2010) — remove the effect? Finally, might the effect depend on the speed of information and updating of the file? For example, if these events took place over a longer amount of time, or if there was more time between stimuli and response, would the effect decrease?

Finally, though this framework may seem to only apply to event completion — as studied here — we suggest that it may provide helpful insight into other kinds of memory distortions. For example, both event completion and representational momentum require dynamic event representations. In event completion, object persistence seems to underlie this dynamicity; similarly, perhaps in representational momentum, representing an object as dynamic requires representing its persistence. In other words, when we see a still image of a melting ice cube, we recall it as more melted than it really appeared (Experiment 3 of Hafri et al., 2022). Thus, perhaps even a static image of an object elicits persistent, dynamic representations that bring about representational momentum, such that disrupting the persistence of the object would consequently disrupt representational momentum (or other related effects) for that object.

What even is "object persistence"?

Though object persistence is among the most foundational object concepts in psychology, its definition is ambiguous and often context-dependent: Object persistence in the context of infant cognition may mean something very different from object persistence in the context of multiple object tracking. And both may differ from what we take object persistence to mean here. The similarities (and differences) in these notions are important to highlight, as they both clarify our proposal and uncover important directions for future work.

One of the first distinctions that arise concerns whether 'object persistence' is about the persistence of *the* object, or just the persistence of *an* object. In our case, we take object persistence to mean persistence of *the* object — i.e., the object shown in the event. In this way, we take presenting a probe frame with a different object (which removes event completion) to be a violation of object persistence. Indeed, under the view that object persistence implies the persistence of *an* object, then the replacement lure frames in Experiment 8 would not be a violation of persistence (given that both contain *an* object), leaving us with no explanation for the observed effect. But in many other cases persistence is taken to mean the persistence of *an* object. For example, a continuously moving object that changes behind an occluder is 'persistent' insofar as it is individuated as a single object, both by infants (Spelke et al. 1995; Xu & Carey, 1996) and by animals (e.g., rhesus macaques; Flombaum et al., 2004). Similarly, object location may be more important than shape and color to object individuation when objects are hidden (Newcombe et al., 1999).

Even within the "persistence of *an* object" view, differing notions of persistence exist. For example, one simple definition posits that one represents an object as persisting over time if an object at time point *t1* is similar enough to an object at time point *t2* (e.g., in terms of object description). Another view requires checking the spatiotemporal continuity of that object over *t1* and *t2*; and another view depends on whether the object category at *t1* matches the object category at *t2* (for review on these three views, see Rips et al., 2006).

The paradigms used to discern such differences themselves posit specific ideas about representations of object persistence. For example, multiple object tracking experiments test what sorts of transformations 'destroy' object persistence by positing that a destruction of persistence will impair tracking of the affected object (Scholl & Pylyshyn, 1999; Scholl, 2007). Persistence experiments in infants posit that object persistence affects object individuation as reflected by increased looking time (e.g., Spelke et al., 1995). However, because we are studying a memory distortion (event completion), our methods uncover different signatures of what happens when persistence is abolished; in other words, while multiple object tracking studies and looking time studies measure an object's persistence 'live' during a presentation (or shortly after), we cannot do so in the same fashion because event completion is a memory effect. Though this initially may seem like a disadvantage, examining persistence in a memory task affords the opportunity to tease apart various features that some take to 'compose' persistence. For example, one view of object persistence suggests that persistence "incorporates and extends the principles of continuity and cohesion" and that "the principles of continuity and cohesion represent only two corollaries of a single and more powerful principle of persistence" (Baillargeon, 2008). But here, we can tease apart continuity from persistence by asking what kinds of manipulations affect event completion (and find that continuity does not, as in Experiment 3). Thus, we think the relationship between continuity (or cohesion) and persistence is actually bidirectional: For an object to be continuous (or cohesive), it must persist (i.e., the opposite of the formulation in Baillargeon, 2008). Though such a claim may appear obvious, it permits for the simpler, more impoverished view of object persistence we take here.

By comparing these different notions of persistence, many interesting avenues for future work arise. For example, as suggested above, perhaps representing the persistence of an object also implies representing its dynamicity (e.g., in the case of representational momentum). Thus, might it be possible for event completion to allow for 'new' objects insofar as the previously seen objects are themselves changing? In other words, suppose the first half of an event depicted a monkey head morphing into a soccer ball, and then the second half of the event depicted no object. Would participants fill-in the presence of *both* the monkey head and the soccer ball? Might the representation of change lead them to fill in *any* object? Furthermore, is there a sense in which 'persistence' applies to the event itself, and not just the objects in the event? For example, if a probe frame depicted a different scene type from what was shown in the event, would participants still fill-in the object due to its persistence? Or would the 'scene persistence' (or 'event persistence' more generally) override this expectation? By exploring these questions, we can both disentangle differing notions of object persistence and make progress on the study of such notions in memory distortions.

Conclusion

Exploring the nature of memory distortions provides rich insight into how we represent objects and events. Here, we demonstrate a simple memory distortion akin to event completion where the mind fills-in the presence of an object after it disappears. We show that this distortion survives in the absence of causality, continuity, event familiarity, object familiarity, physical coherence, and event coherence — each of which have been suggested as an underlying cause of such distortions. Contrary to these proposals, we suggest that object persistence may be the simplest and most direct cause of event completion.

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References

Altmann, G., & Ekves, Z. (2019). Events as intersecting object histories: A new theory of event representation. *Psychological Review*, *126*(6), 817.

Baillargeon, R. (1987). Object permanence in 3½-and 4½-month-old infants. *Developmental Psychology*, *23*(5), 655.

Baillargeon, R., Spelke, E. S., & Wasserman, S. (1985). Object permanence in five-month-old infants. *Cognition*, *20*(3), 191-208.

Baillargeon, R. (2008). Innate ideas revisited: For a principle of persistence in infants' physical reasoning. *Perspectives on Psychological Science*, *3*(1), 2-13.

Baker, L. J., & Levin, D. T. (2015). The role of relational triggers in event perception. *Cognition*, *136*, 14-29.

Biederman, I. (1981). Do background depth gradients facilitate object identification?. *Perception*, *10*(5), 573-578.

Bunger, A., Papafragou, A., & Trueswell, J. C. (2013). Event structure influences language production: Evidence from structural priming in motion event description. *Journal of Memory and Language*, *69*(3), 299-323.

Finke, R. A., & Freyd, J. J. (1985). Transformations of visual memory induced by implied motions of pattern elements. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *11*(4), 780.

Flombaum, J. I., Kundey, S. M., Santos, L. R., & Scholl, B. J. (2004). Dynamic object individuation in rhesus macaques: A study of the tunnel effect. *Psychological Science*, *15*(12), 795-800.

Flombaum, J. I., Scholl, B. J., & Laurie, R. (2009). Spatiotemporal priority as a fundamental principle of object persistence.

Freyd, J. J. (1983). The mental representation of movement when static stimuli are viewed. *Perception & Psychophysics*, *33*(6), 575-581.

Freyd, J. J., & Finke, R. A. (1984). Representational momentum. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *10*(1), 126.

Green, E. J., & Quilty-Dunn, J. (2021). What is an object file?. *The British Journal for the Philosophy of Science*.

Hafri, A., Boger, T., & Firestone, C. (2022). Melting ice with your mind: Representational momentum for physical states. *Psychological Science*, *33*(5), 725-735.

Hafri, A., Papafragou, A., & Trueswell, J. C. (2013). Getting the gist of events: recognition of two-participant actions from brief displays. *Journal of Experimental Psychology: General*, *142*(3), 880.

Hafri, A., Trueswell, J. C., & Strickland, B. (2018). Encoding of event roles from visual scenes is rapid, spontaneous, and interacts with higher-level visual processing. *Cognition*, *175*, 36-52.

Hafri, A., Wadhwa, S., & Bonner, M. F. (2022). Perceived distance alters memory for scene boundaries. *Psychological Science*, *33*(12), 2040-2058.

Hubbard, T. L. (1993). The effect of context on visual representational momentum. *Memory & Cognition*, *21*(1), 103-114.

Hubbard, T. L. (1995). Environmental invariants in the representation of motion: Implied dynamics and representational momentum, gravity, friction, and centripetal force. *Psychonomic Bulletin & Review*, *2*, 322-338.

Hubbard, T. L. (2005). Representational momentum and related displacements in spatial memory: A review of the findings. *Psychonomic Bulletin & Review*, *12*, 822-851.

Hubbard, T. L. (2006). Bridging the gap: possible roles and contributions of representational momentum. *Psicologica: International Journal of Methodology and Experimental Psychology*, *27*(1), 1-34.

Hubbard, T. L. (2017). Toward a general theory of momentum-like effects. *Behavioural Processes*, *141*, 50-66.

Hubbard, T. L., & Favretto, A. (2003). Naïve impetus and Michotte's" tool effect": Evidence from representational momentum. *Psychological Research*, *67*(2), 134-152.

Intraub, H., & Richardson, M. (1989). Wide-angle memories of close-up scenes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*(2), 179.

Kibbe, M. M., & Leslie, A. M. (2019). Conceptually rich, perceptually sparse: Object representations in 6-month-old infants' working memory. *Psychological Science*, *30*(3), 362-375.

Kominsky, J. F., Baker, L., Keil, F. C., & Strickland, B. (2021). Causality and continuity close the gaps in event representations. *Memory & Cognition*, *49*, 518-531.

Li, Y., Wang, Y., Boger, T., Smith, K. A., Gershman, S. J., & Ullman, T. D. (2023). An approximate representation of objects underlies physical reasoning. *Journal of Experimental Psychology: General*.

Mathis, A., & Papafragou, A. (2022). Agents' goals affect construal of event endpoints. *Journal of Memory and Language*, *127*, 104373.

Newcombe, N., Huttenlocher, J., & Learmonth, A. (1999). Infants' coding of location in continuous space. *Infant Behavior and Development*, *22*(4), 483-510.

Papafragou, A., Hulbert, J., & Trueswell, J. (2008). Does language guide event perception? Evidence from eye movements. *Cognition*, *108*(1), 155-184.

Papenmeier, F., Brockhoff, A., & Huff, M. (2019). Filling the gap despite full attention: The role of fast backward inferences for event completion. *Cognitive Research: Principles and Implications*, *4*, 1-17.

Peer, E., Brandimarte, L., Samat, S., & Acquisti, A. (2017). Beyond the Turk: Alternative platforms for crowdsourcing behavioral research. *Journal of Experimental Social Psychology*, *70*, 153-163.

Prasad, A., Wood, S. M., & Wood, J. N. (2019). Using automated controlled rearing to explore the origins of object permanence. *Developmental Science*, *22*(3), e12796.

Radvansky, G. A., & Copeland, D. E. (2006). Walking through doorways causes forgetting: Situation models and experienced space. *Memory & Cognition*, *34*, 1150-1156.

Rips, L. J., Blok, S., & Newman, G. (2006). Tracing the identity of objects. *Psychological Review*, *113*(1), 1.

Scholl, B. J. (2007). Object persistence in philosophy and psychology. *Mind & Language*, *22*(5), 563-591.

Scholl, B. J., & Flombaum, J. I. (2010). Object persistence. In B. Goldstein (Ed.), *Encyclopedia of Perception*, Volume 2 (pp. 653-657). Thousand Oaks, CA: Sage Publications.

Scholl, B. J., & Pylyshyn, Z. W. (1999). Tracking multiple items through occlusion: Clues to visual objecthood. *Cognitive psychology*, *38*(2), 259-290.

Spelke, E. S., Breinlinger, K., Macomber, J., & Jacobson, K. (1992). Origins of knowledge. *Psychological Review*, *99*(4), 605.

Spelke, E. S., Kestenbaum, R., Simons, D. J., & Wein, D. (1995). Spatiotemporal continuity, smoothness of motion and object identity in infancy. *British Journal of Developmental Psychology*, *13*(2), 113-142.

Strickland, B., & Keil, F. (2011). Event completion: Event based inferences distort memory in a matter of seconds. *Cognition*, *121*(3), 409-415.

Strickland, B., & Scholl, B. J. (2015). Visual perception involves event-type representations: The case of containment versus occlusion. *Journal of Experimental Psychology: General*, *144*(3), 570.

Trueswell, J. C., & Papafragou, A. (2010). Perceiving and remembering events cross-linguistically: Evidence from dual-task paradigms. *Journal of Memory and Language*, *63*(1), 64-82.

Ünal, E., & Papafragou, A. (2020). Relations between language and cognition: Evidentiality and sources of knowledge. *Topics in Cognitive Science*, *12*(1), 115-135.

Ünal, E., Ji, Y., & Papafragou, A. (2021). From event representation to linguistic meaning. *Topics in Cognitive Science*, *13*(1), 224-242.

Wang, V., Ongchoco, J. D. K., & Scholl, B. J. (2023). Here it comes: Active forgetting triggered even just by anticipation of an impending event boundary. *Psychonomic Bulletin & Review*, *30*(5), 1917-1927.

Wood, J. N., Ullman, T. D., Wood, B. W., Spelke, E. S., & Wood, S. M. (2024). Object permanence in newborn chicks is robust against opposing evidence. *arXiv preprint arXiv:2402.14641*.

Xu, F., & Carey, S. (1996). Infants' metaphysics: The case of numerical identity. *Cognitive Psychology*, *30*(2), 111-153.

Zacks, J. M. (2020). Event perception and memory. *Annual Review of Psychology*, *71*(1), 165-191.

Zacks, J. M., Speer, N. K., Swallow, K. M., Braver, T. S., & Reynolds, J. R. (2007). Event perception: a mind-brain perspective. *Psychological Bulletin*, *133*(2), 273.

Zacks, J. M., & Swallow, K. M. (2007). Event segmentation. *Current Directions in Psychological Science*, *16*(2), 80-84.

Zhou, K., Luo, H., Zhou, T., Zhuo, Y., & Chen, L. (2010). Topological change disturbs object continuity in attentive tracking. *Proceedings of the National Academy of Sciences*, *107*(50), 21920-21924.