Research Article

Psychological Science
2022, Vol. 33(5) 725–735

DOI: 10.1177/09567976211051744
www.psychologicalscience.org/PS

Melting Ice With Your Mind: Representational Momentum for Physical States

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Abstract

When a log burns, it transforms from a block of wood into a pile of ash. Such state changes are among the most dramatic ways objects change, going beyond mere changes of position or orientation. How does the mind represent changes of state? A foundational result in visual cognition is that memory extrapolates the positions of moving objects—a distortion called *representational momentum*. Here, five experiments (N = 400 adults) exploited this phenomenon to investigate mental representations in state space. Participants who viewed objects undergoing state changes (e.g., ice melting, logs burning, or grapes shriveling) remembered them as more changed (e.g., more melted, burned, or shriveled) than they actually were. This pattern extended to several types of state changes, went beyond their low-level properties, and even adhered to their natural trajectories in state space. Thus, mental representations of objects actively incorporate how they change—not only in their relation to their environment, but also in their essential qualities.

Keywords

state changes, intuitive physics, event cognition, memory distortion, visual memory, open data, open materials, preregistered

Received 4/5/21; Revision accepted 8/30/21

The world is dynamic, not static: Objects change, challenging the mind to represent both their stability (as entities that persist over time) and dynamicity (as entities whose appearance may shift from one moment to the next). In solving this challenge, the mind not only encodes an object's present appearance but also predicts its future. For example, when playing catch, we combine our knowledge of the ball's current location with our prediction of where it will go next (Fink et al., 2009; Hecht & Bertamini, 2000). A foundational result in visual cognition demonstrates that this "forward momentum" is so ingrained in object representation that it distorts memory for changing objects: People misremember objects as being displaced forward in time along their trajectories, a phenomenon known as *representational momentum* (Freyd, 1983; Freyd & Finke, 1984; Hubbard, 2005).

However, objects move not only in physical space but also in *state space*: Ice melts, logs burn, grapes shrivel, and so on. Such transformations represent a fundamentally distinct category of change (Aristotle, ca. 350 B.C.E/1930) that differs dramatically from changes in location or orientation. For example, when a ball moves, most of its features remain constant; the relevant change is simply its relation to its external environment. By contrast, state changes are characterized by a complete transformation of an object's internal and external properties: When a log burns or an ice cube melts, its shape, texture, color, and many other essential qualities often change drastically, such that the object's final

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state may barely resemble its initial state. Furthermore, such changes are not uniform transformations of a single image property (e.g., color, size): State changes look different depending on the type of change, such as melting, burning, or shriveling.

How does the mind represent changes of physical state? It has long been known that such changes organize mental representations in a variety of domains, including semantic memory, language, and cognitive development (Croft, 2015; Gropen et al., 1991; Hindy et al., 2015; Jackendoff, 1990; Lakusta & Landau, 2005; Levin, 1993; Muentener & Carey, 2010; Sakarias & Flecken, 2019; Solomon et al., 2015; Talmy, 2000; Vendler, 1957); indeed, it has recently been suggested that these and other changes serve a foundational role in event representations more generally (Altmann & Ekves, 2019). For example, 8-month-old infants show sophisticated knowledge of state changes and the kinds of agents likely to cause them (Muentener & Carey, 2010). State changes also shape linguistic representations, including the syntactic structures that verbs can take and the meanings such structures convey. For example, in English, many state-change verbs—e.g., "melt" or "deform"—participate in causative alternation structures (such that one can transform a sentence such as "I melted the ice" into "The ice melted" while still describing the same event), but other types of verbs do not (e.g., verbs of communication, as in "I told the story" vs. the ungrammatical "The story told"; Jackendoff, 1990; Levin, 1993).

The Present Experiments: Melting Ice in Memory

Whereas it is increasingly understood how state changes are represented in higher-level cognition, it remains unclear to what extent they reach down into more foundational processes of visual cognition and memory. On one hand, researchers have previously speculated that they might (Finke et al., 1986; Freyd, 1987; Hubbard, 2015a, 2015b, 2017b); for example, Finke et al. (1986) suggested that the mind might extrapolate *any* transformation forward in time. On the other hand, it is possible that the variation and complexities of physical state changes might lead the mind to recruit different cognitive processes from other dynamic changes. Here, we explored these possibilities empirically by asking whether mental representations of state changes share a behavioral profile with other dynamic changes.

To address this question, we tested whether state changes exhibit representational momentum, such that memory extrapolates the future appearance of objects undergoing changes of state (Fig. 1). We created physically realistic animations of familiar objects undergoing state changes—ice melting, grapes shriveling, logs burning, and so on—and played them to participants before stopping the animations at a given frame. We predicted that participants would represent such changes dynamically and thus that the last frame they remembered seeing would be "forward in time" relative to the one they actually saw. In other words, we predicted that the mind might proactively melt, shrivel, and burn the objects it encounters, incorporating such extrapolation into memory itself.

In Experiment 1, we explored representational momentum for state changes in the way just described. In Experiment 2, we asked whether such representations are flexible by contrasting forward-playing animations with backward-playing ones. In Experiment 3, we asked whether the mind represents state changes dynamically even without dynamic input, by using static images. Finally, in Experiments 4a and 4b, we replicated the previous results with a forced-choice response method.

Demos of these experiments can be viewed at https://perceptionresearch.org/dynamicstates, so readers can experience these tasks as the participants did. All the experiments were approved by the Johns Hopkins University Institutional Review Board. The sample sizes and analysis plans (as well as other details) for all experiments were preregistered. Data, code, analyses, stimuli, and preregistrations are available at https://osf.io/gz9a3.

Statement of Relevance

Representing and anticipating the changing world is a fundamental challenge for the human mind. One obvious way in which objects change is in position, as when a baseball flies through the air or a car shifts lanes. But objects also change physical state: Ice cubes melt, grapes shrivel, logs burn, and so on. In such state changes, many essential qualities of the object transform. How does the mind represent changes of state? In the present work, we exploited the phenomenon of representational momentum to ask how state changes are represented by the mind. We found that human memory actively distorts or "plays forward" such changes (e.g., melting ice), such that participants in our tasks remembered the objects as more changed (e.g., more melted) than they actually were. Thus, mental representations of a changing world incorporate dynamic information, in surprisingly broad ways.

Experiment 1: Representational Momentum in State Space

Does memory extrapolate the changing states of objects? In Experiment 1, participants were shown

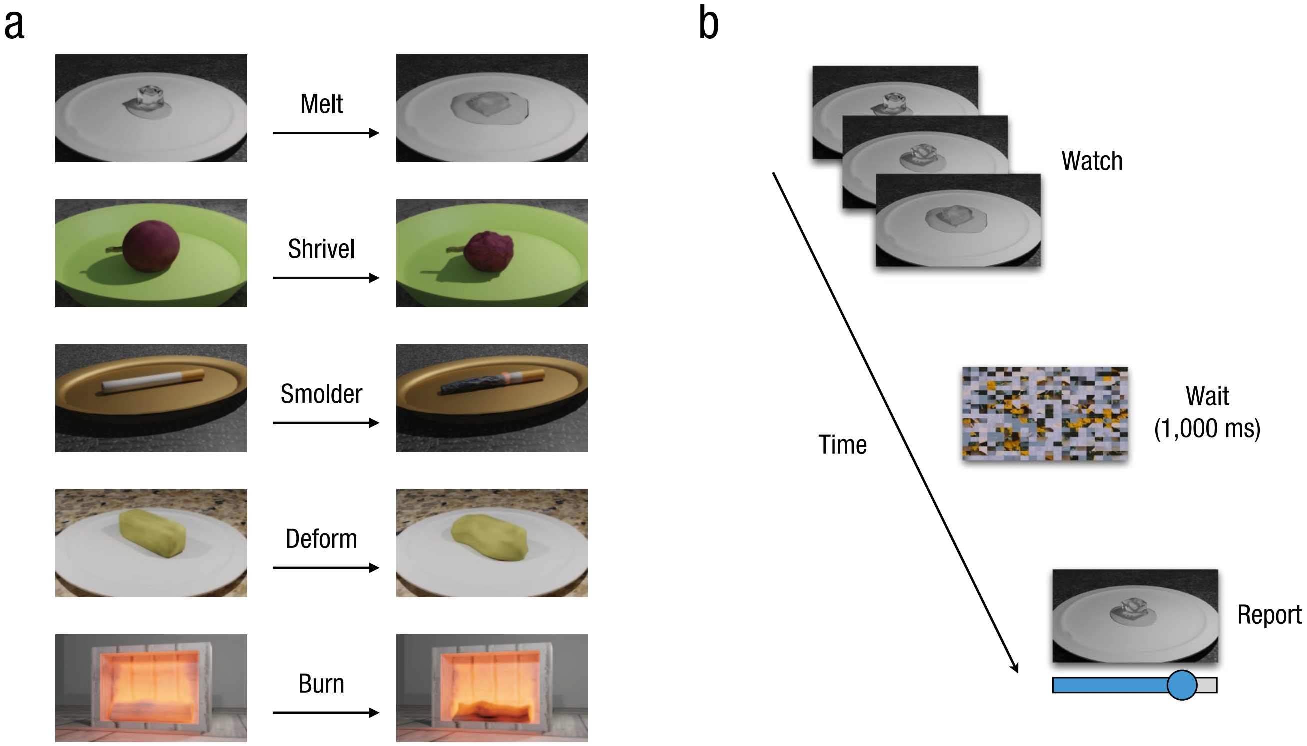

Fig. 1. Design of Experiments 1 through 3. We explored several state changes (a), each involving very different properties. On each trial (b), participants in Experiments 1 and 2 saw an animation of a state change; the animation was stopped before completion and then masked. Participants identified the final frame they had seen using a slider that could advance through all frames of the animation. The procedure was the same in Experiment 3, except that participants saw a single static image rather than an animation.

animations of different objects undergoing changes of state (e.g., ice melting, log burning) and were asked to identify the last frame they saw before the animation was stopped.

Method

Participants. Fifty adult participants were recruited from the online platform Prolific (Peer et al., 2017). This sample size was chosen to be at least as large as those used in previous visual cognition studies of this sort (typically $N < 40$; e.g., De Freitas et al., 2016; Freyd & Finke, 1984; Johnston & Jones, 2006; Thornton, 2014).

Stimuli and procedure. To depict physical state changes while retaining full control of timing and other visual factors, we simulated and rendered state changes under realistic physics using Blender (Version 2.82; https://www.blender.org; Blender Foundation, 2020). We created five different state-change stimuli, each involving very different objects and physical changes: melting, shriveling, smoldering, deforming, and burning (Fig. 1a). Each animation lasted 240 frames and was presented at 30 frames per second (8 s total). Note that although some of the state changes we explored here correspond to transitions between physical states of matter (e.g., a melting ice cube, which transforms from a solid to a liquid), other changes involve chemical reactions (e.g., combustion) or other physical processes, such as osmosis (e.g., shriveling). For present purposes, we consider all such processes to fall under the umbrella term "state changes," though future work could further explore distinctions between these types of change.

All stimuli were 704 × 396 pixels in the participant's Web browser. Because of the nature of online studies, we cannot know exact details such as the viewing distance, screen size, or luminance (etc.) of these stimuli as they appeared to participants. However, any distortions introduced by a given participant's viewing distance or monitor settings would have been equated across all stimuli and conditions for that participant.

On each trial of the experiment (Fig. 1b), participants viewed an animation of one of the state changes, which was stopped before completion and then masked for 1,000 ms with a box-scrambled mask (20 × 20 blocks, randomly selected from seven possible masks of natural scenes). Following this, participants' task was simply to identify the last frame of the animation that they saw before it was stopped. Participants selected the target frame using a slider that stepped through the animation frame by frame. (The starting position of the slider was randomized on every trial.) The left end of the slider

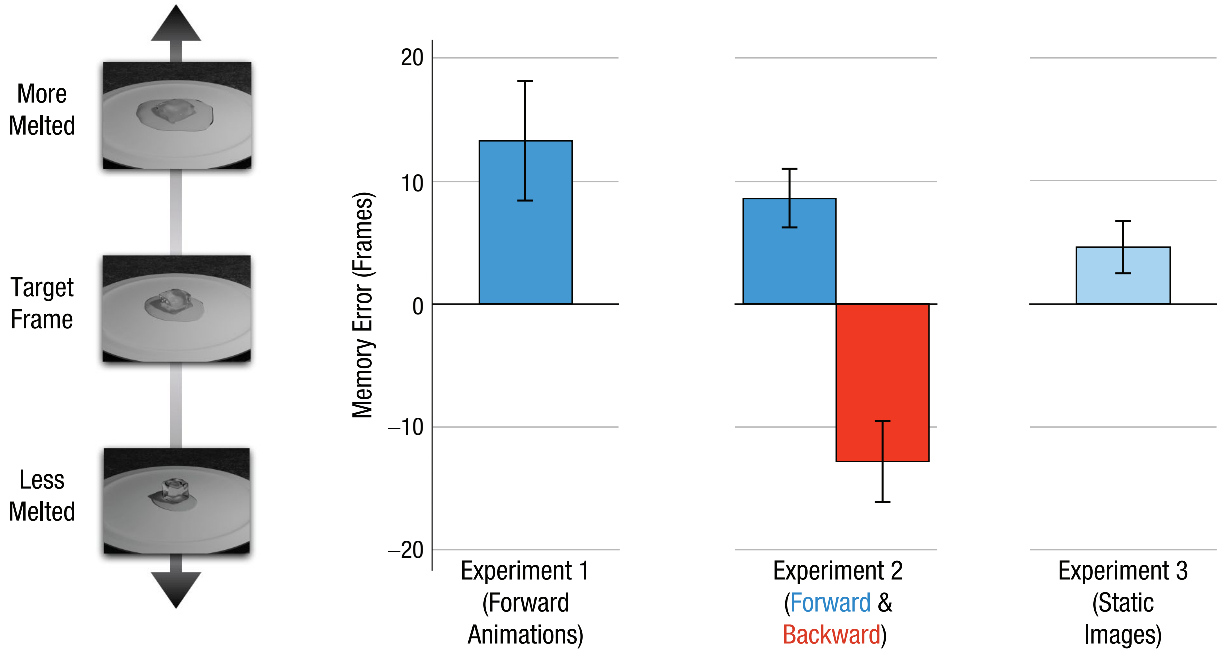

Fig. 2. Results for Experiments 1 through 3. Mean memory error across participants is shown separately for each experiment and condition. Memory error was indexed by taking the signed difference between the frame chosen by participants and the actual target frame. In Experiment 1, participants saw forward animations. In Experiment 2, participants saw forward and backward animations. In Experiment 3, participants saw only a single static frame. Error bars represent 95% confidence intervals.

represented the beginning of the animation, and the right end represented the end of the animation. When satisfied that the image on the screen matched the final frame they had seen earlier in the trial, participants clicked a button to move on to the next trial.

To ensure that the task was clear, we had participants first complete an easy trial during the instruction phase. In this trial, they had to reproduce the exact frame at which an animation was stopped. The target frame to reproduce remained on screen throughout this practice trial (so that the correct answer was clear); participants could not proceed with the experiment until they performed this trial as instructed.

There were three blocks of experimental trials, each containing the five state changes in a random order (15 trials total). Each animation was stopped either 25%, 50%, or 75% before completion (randomized order, once for each state change) and was then masked immediately after it was stopped so the animation did not proceed further. The full animations (and the Blender code to render them) are available on OSF (https://osf.io/gz9a3); demos of this experiment can be viewed at https://perceptionresearch.org/dynamicstates.

For each trial, we calculated the *frame error*: the signed difference between the frame chosen by participants and the actual target frame. For example, if the last frame that appeared was frame 180, a response of 188 would be a frame error of +8. We predicted that participants would misremember the last frame they saw as being further forward in time than it actually was and report it as such, resulting in a positive frame error.

Results

In accordance with our preregistered analysis plan, we excluded participants if they did not contribute a complete data set or if their mean slider responses (averaged across state changes) were not lower for earlier target frames and higher for later target frames. (We reasoned that participants who did not give lower frame responses for earlier target frames were likely not performing the required task.) There were 43 participants after these exclusions.

As predicted, we observed a significant positive frame error: Participants reported a frame further forward in time relative to the true final frame ($M = 13.25$ frames out of 240, or 442 ms out of 8 s of the animation), $t(42) = 5.34$, $p < .001$, $d = 0.81$, 95% confidence interval (CI) = [8.24, 18.26] (see Fig. 2). In other words, participants reported the ice as more melted than it really appeared. This pattern occurred for every type of state change shown—melting: $M = 21.99$, $t(42) = 6.08$, $p < .001$, $d = 0.93$, 95% CI = [14.69, 29.29]; shriveling: $M = 7.63$, $t(42) = 2.19$, $p = .034$, $d = 0.33$, 95% CI = [0.59, 14.66];

smoldering: $M = 8.96$, $t(42) = 4.41$, $p < .001$, $d = 0.67$, 95% CI = [4.86, 13.07]; deforming: $M = 7.67$, $t(42) = 2.00$, $p = .052$, $d = 0.31$, 95% CI = [−0.06, 15.40]; burning: $M = 20.00$, $t(42) = 5.18$, $p < .001$, $d = 0.79$, 95% CI = [12.21, 27.80].

Moreover, the results were not driven by a mere tendency to respond toward the slider's center: Although frame error was highest for animations that stopped earlier ($M = 22.69$), $t(42) = 5.60$, $p < .001$, $d = 0.85$, 95% CI = [14.52, 30.86], we still found positive frame errors for animations stopped halfway through ($M = 13.00$), $t(42) = 4.34$, $p < .001$, $d = 0.66$, 95% CI = [6.95, 19.05]. We even observed a positive trend for animations that stopped at frames corresponding to the later end of the slider ($M = 4.07$), $t(42) = 1.92$, $p = .061$, $d = 0.29$, 95% CI = [−0.20, 8.33], where a tendency to respond toward the center of the slider should have favored the opposite effect (stacking the deck against our prediction). These results suggest that the mind extrapolates state changes beyond what is actually observed: representational momentum for state changes.

Experiment 2: Flexibility of Extrapolation

Some changes of state are irreversible: An ice cube can melt into a puddle, but a puddle cannot "unmelt" into an ice cube. (The best it can do, perhaps, is freeze in place.) Does the mind flexibly extrapolate state changes along directions we have rarely (if ever) encountered (i.e., not only melting but also unmelting)? In Experiment 2, we tested this by including trials in which state-change animations played in reverse; in such backward animations, participants saw a puddle unmelt into an ice cube.

Method

Fifty new participants were recruited for Experiment 2, which was identical to Experiment 1 except for the addition of three blocks of experimental trials in which the animations played in reverse (with order of forward and backward sets counterbalanced across participants). We also counterbalanced slider direction (left = earlier vs. right = later, or vice versa) across participants to control for possible directional biases in using the slider.

Results

In accordance with our preregistered analysis plan, we excluded participants if they did not contribute a complete data set or if their mean slider responses (averaged across state changes) were not lower for earlier target frames and higher for later target frames. This left 48 participants.

We again observed positive frame errors for forward animations ($M = 8.61$ frames), $t(47) = 4.95$, $p < .001$, $d = 0.71$, 95% CI = [5.11, 12.12] (see Fig. 2), consistent with the results of Experiment 1. Intriguingly, backward animations also showed frame errors along the direction of the animation; these were negative frame errors, as they were in a direction opposite to the physically natural direction depicted in forward animations ($M = −12.81$ frames), $t(47) = −7.34$, $p < .001$, $d = −1.07$, 95% CI = [−9.32, −16.30]. In other words, when shown an animation of ice unmelting (a backward animation), participants remembered the ice as more unmelted than it really was. For backward-playing animations, this provides evidence for representational momentum in the same way that positive frame errors in forward-playing animations provide evidence for representational momentum.[1]

Beyond demonstrating flexible representation of state changes, these results also suggest that our earlier findings were not driven by mere familiarity with a given pattern of physical change. If the memory biases observed in Experiment 1 were simply driven by prior experience seeing ice cubes melt and logs burn (and so on), one would not have expected the same effects to arise for unmelting and unburning. So the fact that similar effects do arise for unmelting and unburning suggests that the effects go beyond simply recreating events one has seen before and instead involve actively representing and extrapolating state changes as they occur.

Experiment 3: Static Images

We have suggested that the present effects arise because the mind represents state changes per se. But our previous results might be explained by a lower-level mechanism. In particular, our dynamic animations necessarily included not only high-level information about changing states but also lower-level visual changes that are inevitably correlated with those state changes (e.g., optic flow or motion energy). In that case, the effects might not have been driven by participants extrapolating the state changes per se (e.g., mentally melting the ice) but rather by ordinary representational momentum for the motion present in the animations—such as the expansion of the puddle formed by the melting ice.

In Experiment 3, we addressed this possibility by asking whether a single static frame can elicit representational momentum in state space, as has been previously shown for location memory (e.g., Bertamini, 1993; Finke et al., 1986; Freyd, 1987). This design not only ruled out effects of low-level motion but also allowed us to investigate whether the mind privileges one direction over the other (e.g., representing the physically natural forward direction—melting, rather than unmelting—by default).

Method

Participants. One hundred new participants were recruited. This sample size was larger than in the previous two experiments because we expected the representational-momentum effects to be more subtle for static than dynamic stimuli.

Stimuli and procedure. The stimuli, task, and conditions of Experiment 3 matched those of Experiment 1, except that participants viewed a single static frame (for 1,000 ms) instead of dynamic animations. Moreover, we included three 50%-frame trials per state change rather than just one, and we analyzed only those trials (and preregistered this analysis), because we expected that a tendency to respond toward the slider's center—which would result in biased results at non-50% frames—might obscure the more subtle representational-momentum effects we anticipated for static images. The 25%-frame and 75%-frame trials (one of each per state change) were included in the experiment (but were not analyzed) to decrease the possibility that participants would realize the frames of interest were always at exactly 50%. Thus, there were five blocks of stimuli, each containing the five state changes in a random order (25 trials total). For each state change, the order of the target frame image (25%, 75%, or the three 50% frames) was randomized. As in Experiment 2, we also counterbalanced slider direction (left = earlier vs. right = later, or vice versa) across participants.

Results

In accordance with our preregistered analysis plan, we excluded participants if they did not contribute a complete data set or if their mean slider responses (averaged across state changes) were not lower for earlier target frames and higher for later target frames. This left 94 participants.

We again observed a positive frame error: Even when shown only a single static image from the middle of the state-change events, participants misremembered the state changes in their physically natural directions ($M = 4.64$ frames), $t(93) = 4.06$, $p < .001$, $d = 0.42$, 95% CI = [2.37, 6.92] (see Fig. 2).[2] Thus, (a) representational momentum arises in state space even without any lower-level dynamic cues to indicate a direction of change, and (b) the extrapolated direction in state space is *forward* by default, suggesting that this process incorporates physically natural constraints on such changes.

Experiments 4a and 4b: Forced Choice

The previous experiments suggested that the mind extrapolates state changes forward, even without dynamic input suggesting such changes. However, by using a slider as the response modality, these experiments may have allowed participants to "play" the animation forward, such that the "momentum" we observed may have had nothing to do with a memory distortion in state space but rather with the actual responses they gave. (Indeed, on this alternative account, the effect could literally be due to the physical momentum of participants' hands moving a mouse!) In a final set of experiments, we replicated Experiment 3 using a forced-choice paradigm to rule out even this alternative.

Method

The design of Experiments 4a and 4b was similar to that of Experiment 3 in that participants observed a single static frame on each trial. However, unlike in Experiment 3, after the mask appeared, participants were shown two possible frames (rather than a slider), and they were instructed to choose the frame that matched the target frame that they had observed earlier in the trial (Fig. 3a). In fact, neither frame was correct (though participants were not informed of this): One was always earlier than the true target frame, and the other was always later than the true target frame (by the same magnitude in each direction). We asked whether extrapolation would still be observed here, despite the difference in probing method.

Participants. Two groups of 100 participants each were recruited from Prolific for both Experiment 4a and Experiment 4b (i.e., 200 participants total). We chose sample sizes of 100 in both experiments to match the 100 used in Experiment 3, given that both experiments contained static stimuli instead of dynamic stimuli.

Stimuli and procedure. In contrast with the slider-based response method of Experiments 1, 2, and 3, the method of probing memory here was a two-alternative forced-choice task. The two options were either earlier or later than the target frame (by 30 frames in each direction, determined via pilot testing).

To ensure that the change in response method (from slider to forced choice) was the only difference between Experiment 4a and Experiment 3, we kept the same design in Experiment 4a as in Experiment 3, including the sampling and analysis of frames. Participants viewed four 50%-frame trials per state change rather than just three. As in Experiment 3, we analyzed only those

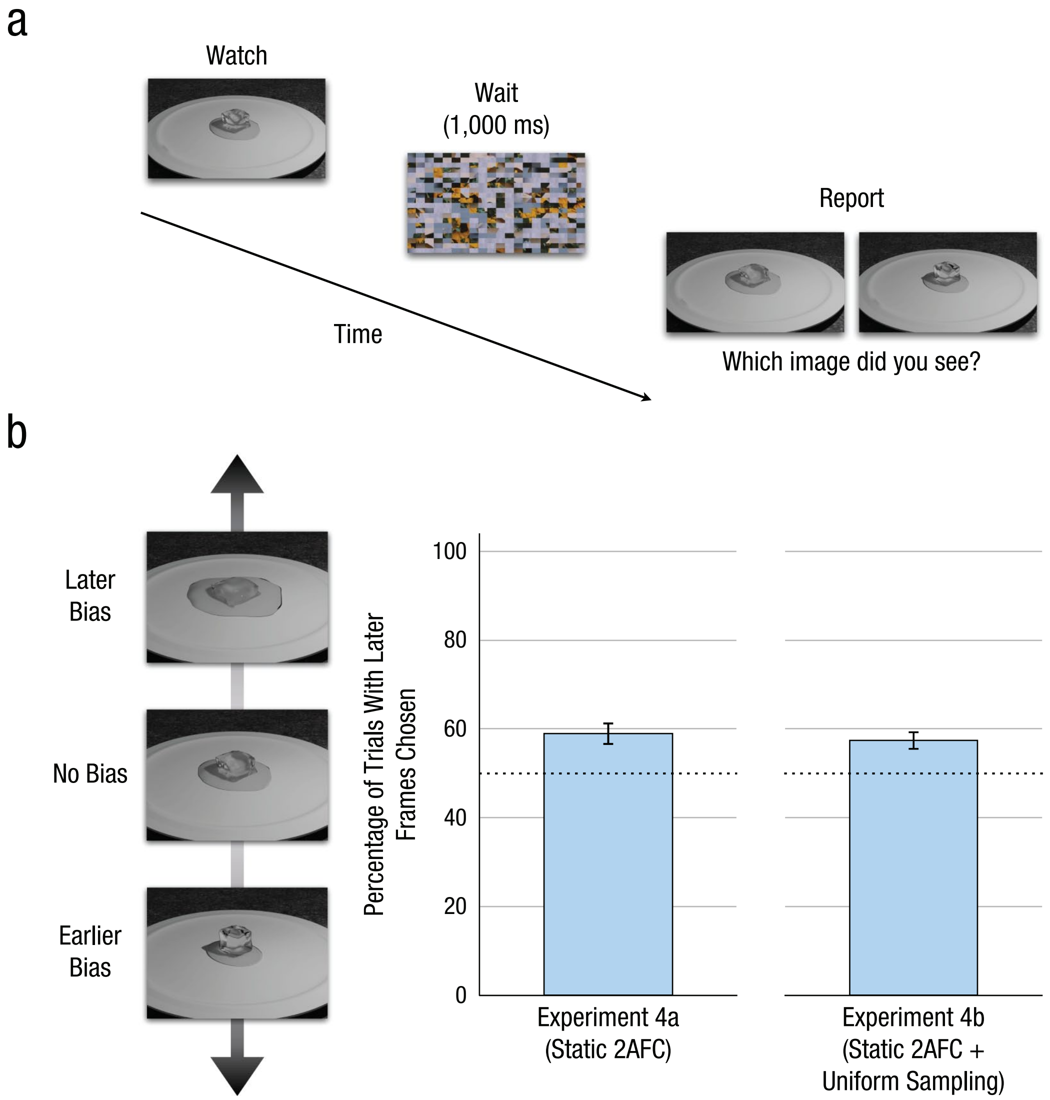

Fig. 3. Design and results of Experiments 4a and 4b. On each trial (a), participants saw a single static image of a state change; the target image was masked, and participants were tasked with selecting the target image from between two options. Participants were not informed that both frames were incorrect: One was earlier than the target frame, and one was later. The mean across participants of the percentage of later frames that were chosen (b) is shown separately for each experiment. In Experiment 4a, results are from the 50% frame (the middle of the state-change events, as in Experiment 3), whereas in Experiment 4b, results reflect uniform sampling across the entire range of frames. Error bars represent 95% confidence intervals. 2AFC = two-alternative forced choice.

50%-frame trials (and preregistered this analysis); the 25%-frame and 75%-frame trials (one of each per state change) were included in the experiment to decrease the possibility that participants would realize that the frames of interest were always at exactly 50%. There were two epochs in the experiment, each containing three blocks (with each block containing the five state changes in random order). Each epoch contained two 50% trials for each state change; the third trial for each state change in the epoch, either 25% or 75%, was randomly assigned (e.g., for melting, the 25% trial may have appeared in the first epoch and the 75% trial in the second; for smoldering, the 75% trial may have appeared in the first epoch and the 25% trial in the second). Thus, there were 30 trials in total. Position of the later frame, left or right, was counterbalanced for each state change and epoch (i.e., the later image was on the left for half the trials of each state change and epoch).

Experiment 4b differed more substantially: In addition to using the forced-choice procedure described above, it also eliminated any selective sampling in both the experimental design and the analyses, in order to ensure that the effects were not particular to potential idiosyncrasies of the single 50% frame analyzed. In this experiment, we sampled from a uniform distribution of frames for every participant and state change: On any given trial, participants saw a frame chosen randomly from the full range of possible frames for a state change. Then, as in Experiment 4a, they had to choose between two frames that were offset by 30 frames in each direction from the true target frame. As in Experiment 4a, there were six blocks, each containing one static frame of each state change in a random order. The target frames shown for each state change were sampled from a uniform distribution between Frames 31 and 209; crucially, this ensured that the +30 and −30 offsets for probe frames would stay within the bounds of the 240 total frames for each state change, and thus it would be possible to choose either the earlier or later option even at the extremes. Frames were sampled such that the mean frame shown for each state change was 120 (or 50% through the state change). This average of 120 was accomplished by choosing three frames randomly for each state change and then setting the remaining three frames to be 240 minus the initial three frames chosen. For example, if the frames chosen for ice melting were 36, 97, and 170, then Frames 204, 143, and 70 were also included, which together average to 120. The order of these frames was randomized within blocks.

We expected that, when forced to choose between an earlier and later frame, participants would choose the later frame more often than the earlier frame.

Results

In accordance with our preregistered analysis plan, we excluded trials with a response time that was considered too fast (< 400 ms). (This was conservative, as it excludes only trials in which it was unlikely that the participant could have fully registered the images and planned their response.) We also excluded participants if they did not contribute a complete data set or if more than 10% of their trials were excluded for being too fast, reasoning that participants with too many fast responses were likely not performing the required task. This left 99 participants in each of Experiments 4a and 4b. Considering these remaining participants, we excluded 0.70% of trials for being too fast in Experiment 4a and 0.17% of trials for being too fast in Experiment 4b.

We once again observed evidence that memory for objects changing state is extrapolated forward in time. Even when shown only a single static image from the state-change events in Experiment 4a, participants misremembered the changes as being in their physically natural direction, more often selecting the later probe frame than the earlier probe frame (M = 58.86% of trials on which the later probe frame was selected), $t(98) = 7.44$, $p < .001$, $d = 0.75$, 95% CI = [56.50%, 61.23%] (see Fig. 3b). Furthermore, this was not just a result of seeing the middle of the state-change events; in Experiment 4b, in which participants saw frames that were chosen uniformly across the entire range of state-change frames, they again selected the later probe frame more often than the earlier probe frame (M = 57.37% of trials on which the later probe frame was selected), $t(98) = 7.41$, $p < .001$, $d = 0.74$, 95% CI = [55.39%, 59.34%] (see Fig. 3b). Whereas the results of Experiments 1 through 3 may have been explained by the natural biases of the slider, this possibility cannot explain the results in the current experiment, in which participants were forced to choose between two discrete options. Thus, even with a different response method, participants demonstrated representational momentum for state changes.

General Discussion

The present experiments suggest that state-change representations share a behavioral profile with more traditionally studied dynamic event representations, in that memory distorts such changes forward in time. The dynamic nature of object representation is thus surprisingly general: Our minds represent not only where an object is likely to have moved but also how an object is likely to have *transformed*.

Dynamic distortions

Importantly, the memory distortions observed here go beyond merely predicting the future states of changing objects. It is not so surprising that one can predict how a melting ice cube will look at some later time, just as one can predict the future appearance of all sorts of objects and events. What is distinctive about the present results, however, is that participants actively mistook a later stage of these state changes for what they actually observed. Thus, even if the representational-momentum effects reported here were driven by predictions of some sort (Hubbard, 2019), they go beyond simply making those predictions and instead intrude on more foundational processes of memory itself. In other words, these effects are a case of inferences causing memory distortions for state changes in a manner similar to memory distortions for physical locations (Freyd, 1987; Hubbard, 2006).

Moreover, the existence of representational momentum for state changes was not a foregone conclusion. On one hand, representational momentum is clearly established for location (e.g., Freyd, 1983; Freyd & Finke, 1984; for a review, see Hubbard, 2005), and it has been extended to other properties, such as pitch (Freyd et al., 1990; Johnston & Jones, 2006), action (Chatterjee et al., 1996; Hudson et al., 2016; Verfaillie & Daems, 2002), and even social position (Kakkar et al., 2019). On the other hand, it has not been conclusively demonstrated for other continuous properties, such as luminance (Brehaut & Tipper, 1996), hue (Callahan-Flintoft et al., 2020), and emotional expression (Thornton, 2014). (Indeed, the lack of forward momentum in these cases is another reason that the present effects go beyond mere prediction, because it is quite easy to predict the future luminance value of an object that is smoothly increasing in brightness.) Thus, not only is representational momentum for state changes a genuinely new discovery about how such changes are represented, but its existence also supports theories holding that the nature of dynamic representation is quite general (Finke et al., 1986; Freyd, 1987; Hubbard, 2015a, 2015b, 2017a, 2017b).

Intuitive reasoning about physical states

The present results add to a growing literature on intuitive physical reasoning. Recent work reveals that the mind represents future arrangements of physical scenes, as if pressing "play" on a simulation of that scene (e.g., block towers; Battaglia et al., 2013; Firestone & Scholl, 2016; Fischer et al., 2016; Kubricht et al., 2017; Ullman et al., 2017; see also Guan & Firestone, 2020). Our findings go beyond these sorts of results in at least two ways. First, they suggest that such intuitive physical reasoning can operate not only over the arrangement and movement of objects but also over their physical composition. And second, they suggest that the cognitive mechanisms underlying such intuitions not only support higher-level inferences about how physical scenes will unfold but also actively distort memory for them. The effects reported here may even be considered a kind of "future" analog of recent findings that perception represents the causal history of objects (Chen & Scholl, 2016).

Future work could explore whether state changes in physical reasoning are represented in ways that are less reflective of the continuous nature of real-world changes and more similar to how state changes are represented in other domains (such as language), where a core distinction is made between gradual, process-based changes of the kind explored here (e.g., "the balloon expanded") and instantaneous transitions (e.g., "the balloon exploded"; Croft, 2015; Vendler, 1957). For example, even if one watches a slowed-down video of an exploding balloon to see the pieces scatter, the mind may still treat this state change as categorical and instantaneous. Perhaps there are even "attractors" in state space, much like those that have been established in physical space (e.g., cardinal biases; Huttenlocher et al., 1991; Newcombe & Huttenlocher, 2000; Palmer, 1980; Tversky, 1981). Indeed, prior work suggests that certain locations in state space are particularly salient in the mind (Croft, 2015; Lakusta & Landau, 2005; Sakarias & Flecken, 2019). In that case, one might imagine that nearly melted ice gets treated as fully melted by the mind or that an ice cube that has only barely begun melting may get mentally reverted to an unmelted ice cube. Some exploratory analyses from Experiment 4 are in line with this intriguing possibility (see the supplementary material available at https://osf.io/uskcz/), which may be investigated in future work.

General implications and open questions

The implications of these results may go beyond new findings about state changes or memory distortions by interacting with more general theories of event perception and memory—for example, event-segmentation theory (Zacks et al., 2007) or the theory of event coding (Hommel et al., 2001; see also Kim et al., 1995; for a review, see Zacks, 2020). One uniting factor of such proposals is that the mind represents or detects cognitively salient aspects of the event at hand. Our results add to this literature by suggesting that surprisingly complex state changes—including fundamental changes to material or matter—not only are incorporated into higher-level reasoning about events that we have experienced (or otherwise represented) but also play an active role in on-line event representation.

An open question concerns the generality of such state-change representations in the mind. We found that the directionality of state changes is quite flexible, even for directions rarely encountered (e.g., unmelting ice), but a related question is whether state-change representations are constrained by the kinds of objects that usually undergo such changes. For example, grapes shrivel differently from other fruits, and ice does not normally shrivel at all, yet state changes such as shriveling are in principle quite general, applicable to many types of objects (just like affine changes such as rotation and translation; Schmidt et al., 2016; Ward et al., 2018). Perhaps representational momentum for state changes would also generalize to rarely observed associations between objects and state changes, such as shriveling butter or smoldering ice.

Concluding remarks

The discovery of representational momentum for state changes complements related work in domains such as cognitive development, semantic memory, and linguistics (Altmann & Ekves, 2019; Hindy et al., 2015; Jackendoff, 1990; Lakusta & Landau, 2005; Levin, 1993; Muentener & Carey, 2010), extending this research for the first time into the domain of visual cognition and memory. By demonstrating that the mind dynamically represents the physical changes of objects—and even incorporates their probable future states into memory—we show that state changes not only organize how we think and speak about the world but also constrain how we remember it in the first place.

Transparency

Action Editor: Marc J. Buehner
Editor: Patricia J. Bauer
Author Contributions

A. Hafri and T. Boger contributed equally to this article. All authors jointly designed the experiments. T. Boger programmed and ran the experiments and analyzed the data with input from A. Hafri and C. Firestone. All authors jointly wrote the manuscript and approved the final version for submission.

Declaration of Conflicting Interests

The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.

Funding

This work was supported by National Science Foundation Grant No. BCS-2021053 awarded to C. Firestone and National Science Foundation Directorate for Social, Behavioral and Economic Sciences (SBE) Postdoctoral Research Fellowship No. SMA-2105228 awarded to A. Hafri.

Open Practices

All data, analysis code, and materials have been made publicly available via OSF and can be accessed at https://osf.io/gz9a3. The design and analysis plans for all the experiments were preregistered on AsPredicted (copies are available at https://osf.io/gz9a3). This article has received the badges for Open Data, Open Materials, and Preregistration. More information about the Open Practices badges can be found at http://www.psychologicalscience.org/publications/badges.

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Acknowledgments

For helpful discussion and/or comments on drafts of this article, the authors thank John Trueswell and members of the Johns Hopkins University Perception & Mind Laboratory.

Notes

1. Although a trend for greater frame errors in the direction of animation was observed for backward compared with forward animations in Experiment 2, $t(47) = 1.76$, $p = .085$, $d = 0.25$, 95% CI = [−0.60, 9.00], results from Experiments 3, 4a, and 4b suggest that the default direction of change in the mind is "forward" (i.e., the physically natural direction of change).

2. Though we report only our preregistered analysis of the 50%-frame trials here, we present analyses for all frames (for this and all experiments) in the supplementary material available at https://osf.io/uskcz/. The results of all such analyses were consistent with the effects we report here—that is, representational momentum for state changes—regardless of whether we did or did not include data from all trials.

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