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Eye-tracking mental simulation during retrospective causal reasoning

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Abstract

There are conflicting theories about how people reason through cause and effect. A key distinction between two prominent accounts pertains to whether, in judging an event's causal relevance, people preferentially consider what actually happened (as predicted by process theories) or whether they also consider what could have happened under different conditions (as predicted by counterfactual theories). Toward adjudicating between these theories, the current work used eye tracking and Gaussian Process modeling to investigate how people form causal judgments retrospectively and in the absence of ongoing visual input. Participants played a virtual ball-shooting game: after choosing to move left or right, they encoded a video of the actual outcome and then were prompted to mentally simulate either (a) what actually happened, (b) what could have happened, or (c) what caused the outcome to happen while looking at a blank screen. During causal judgment, we found evidence that participants visually mentally simulated counterfactual possibilities: they moved their eyes in similar patterns as when they imagined a counterfactual alternative. Altogether, these results favor counterfactual theories of causal reasoning, demonstrate how visual mental simulation can support this reasoning, and provide a novel methodological approach for using eye movements to investigate causal reasoning and counterfactual thinking more broadly.

Keywords: causal judgment; mental simulation; counterfactual thinking; eye-tracking

Introduction

There are conflicting explanations of how people make causal judgments. *Process theories* argue that a cause must transfer force to its effect, and so people only need to consider the actual interaction between the candidate cause and the effect to judge causal relevance (Dowe, 2000; Salmon, 1997; Wolff, 2007). *Counterfactual theories* instead argue that a cause makes a difference to its effect, and so to make a causal judgment, people must compare what actually happened to what could have happened if the candidate cause had been absent or altered in some way (Hume, 1739; Lewis, 1974; Gerstenberg, Goodman, Lagnado, & Tenenbaum, 2021; Goldvarg & Johnson-Laird, 2001; Pearl, 2009; Quillien, 2020). Thus, determining the degree to which people consider information about the actual event relative to information about counterfactual possibilities has been a critical focus of empirical investigations of causal judgment (Cheng, 1997; Icard, Kominsky, & Knobe, 2017; Lagnado, Gerstenberg, & Zultan, 2013; Waldmann & Hagmayer, 2013).

Toward adjudicating between process and counterfactual theories, Gerstenberg, Peterson, Goodman, Lagnado, and Tenenbaum (2017) used eye movements to measure what information participants looked at during an event to later formulate a causal judgment. Specifically, participants watched an event of two balls moving around a screen and colliding. They then answered questions about (a) whether B actually scored, (b) whether B would have scored if A were absent, or (c) whether A was causally relevant to B scoring or missing the goal. The findings showed that, prior to the collision, participants who answered counterfactual and causal questions about the event had a greater tendency to fixate where objects were about to move compared to participants who answered questions about the actual outcome. Moreover, this tendency predicted judgments of A's causal relevance to the outcome.

The findings from Gerstenberg et al. (2017) suggested that participants mentally simulated something about B beyond its actual movements. Gerstenberg et al. (2017) interpreted such simulations as being counterfactual in nature; their counterfactual simulation model predicted causal judgments by assuming that participants used an intuitive understanding of physics to mentally simulate where B would have moved in the absence of A (Gerstenberg et al., 2021; Gerstenberg & Icard, 2020; Gerstenberg & Stephan, 2021). However, specifically when eye movements are recorded while objects are in motion and perceptually available in real time, there are some concerns as to whether eye movements can truly distinguish counterfactual thinking from other cognitive processes for understanding object motion, such as anticipatory extrapolations (e.g., Luu & Howe, 2015), heuristics (e.g., Kozhevnikov & Hegarty, 2001), qualitative spatial reasoning (e.g., Forbus, 2014), or rapid visual processing (e.g., Firestone & Scholl, 2017). Indeed, these alternative interpretations are often considered in arguments against mental simulation as a cognitively plausible account of physical reasoning more generally (Davis & Marcus, 2015; Kubricht, Holyoak, & Lu, 2017).

The current study

Toward further adjudicating between process and counterfactual theories in the current work, we predicted that eye movements could be used to investigate causal judgment and episodic counterfactual thinking *in the absence of ongoing visual input*. Visual mental simulations are frequently accompanied by reports of mental imagery, which is known to recruit similar neural activation patterns as external visual perception (Clement, 1994; Pearson, 2019). Moreover, past re-

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search shows that when engaging in visual mental simulation or "mental imagery", people tend to move their eyes as if they were actually perceiving the image even in the absence of ongoing perceptual input (e.g., Altmann, 2004; Brandt & Stark, 1997; Richardson & Spivey, 2000). Further, these *retrospective eye movements* tend to reinstate the same looking patterns as during initial viewing, and this tendency is correlated with better recall of the visual information, the self-reported vividness of the mental image, and with similarities in brain activation patterns between initial encoding and later imagery (Bone et al., 2019; Gurtner, Bischof, & Mast, 2019; Laeng & Teodorescu, 2002). Thus, it has been argued that retrospective eye movements may facilitate memory retrieval of simulated content (e.g., Bochynska & Laeng, 2015; Johansson & Johansson, 2014; Laeng, Bloem, D'Ascenzo, & Tommasi, 2014).

In light of the research on eye movements and mental simulation, we asked participants to play a ball-shooting game by moving a ball (or a goalie) in an attempt to score (or defend) a goal. After watching and encoding a video of the outcome, participants looked at a blank screen and mentally simulated either (a) the actual outcome, (b) a counterfactual outcome, or (c) the causal relationship between the participant's movement and the outcome. We then compared the eye movements across these conditions to infer what, if anything, participants mentally simulated during causal reasoning. We designed our videos to ensure that counterfactual alternatives were spatially distinct along the vertical mid-line of the display from future hypothetical outcomes. For example, if the ball actually moved to the right on a given trial, its counterfactual movement would be moving to the left. This design helped to disambiguate actual from counterfactual movements as well as counterfactual movements from future projected movements. We also recorded eye movements during both encoding and during retrospective mental simulation to conceptually isolate retrospective causal judgment. That is, at encoding participants did not know what they would later need to mentally simulate. Given this design, we predicted no difference in eye movements during encoding between trials in which participants later mentally simulated the actual outcome, a counterfactual outcome, or the causal relationship between their object and the outcome. During later mental simulation, however, we did predict differences across these conditions: when mentally simulating the actual outcome, we predicted that participants would look at locations where the objects had actually moved, but when mentally simulating a counterfactual alternative, participants would look at locations where the objects would have moved in the imagined counterfactual. Critical to adjudicating between process theories and counterfactual theories, our main focus was where participants looked when making a causal judgment. Process theories predict that people only need to consider what actually happened when making causal judgments. So, process theories predict that participants will look at locations where the objects had actually moved. Counterfactual theories, however, predict that people need to compare what actually happened with what would have happened in a counterfactual alternative. So, counterfactual theories predict that participants should also look at locations where the objects would have moved in the simulated counterfactual.

Methods

Participants

To roughly match the statistical power of (Gerstenberg et al., 2017), we recruited 41 participants. Participants were 18-35 years old, from Duke University and the surrounding community, provided informed consent in accordance with the Duke University Institutional Review Board, and were compensated $12/hour for participating in the experiment.

Materials

The stimuli consisted of video clips generated with JBox2D, which were presented centered on a 24-in LCD monitor with a screen refresh rate of 59 Hz. Viewing distances of 94-cm were maintained with a desk-mounted chin and forehead rest. Therefore, the videos subtended 13° x 10° of visual angle.

The videos contained three objects (illustrated in Figure 1A) that move around and interact: a red goal, a blue circular ball, and an orange circular goalie. In the videos, the ball and goalie always started centered horizontally. Next, the ball and goalie simultaneously moved left or right, such that the ball either entered the goal or was blocked by the goalie. Both objects always moved at the same angle, time, and speed on each trial. The orientation of the display varied by 180° on half of trials, resulting in an upward and downward orientation, with presentation order counterbalanced across subjects. All materials and code are available via the Open Science Framework.

Eye movements were tracked using the desk mounted EyeLink 1000 Plus (SR Research, Inc.), sampled at a rate of 500 Hz. The eye-tracker was calibrated using a nine-point calibration at the beginning of the study. A one-point calibration was used before each trial to correct for drift in eye tracking validity that can occur naturally over time. All responses were registered with a standard computer mouse click.

Procedure

After providing written consent, participants were randomly assigned to either the offensive or the defensive position conditions, which determined the participants' objective: offensive participants controlled the ball and were instructed to "Shoot the ball and score as many times as possible", whereas the defensive participants controlled the goalie and were instructed to "Defend the goal and block the ball as many times as possible." Participants then received detailed task instructions and watched several instructional videos to learn the starting position of each object, the speed and angle by which they moved, and how they interacted.

After following the 9-point calibration procedures, the experiment began. Participants started each trial by first deciding whether to move their object to the left or right (Figure

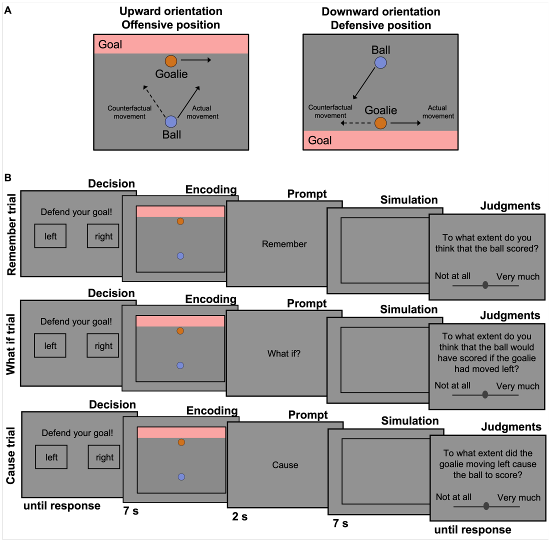

Figure 1: *A*) Example video display orientations for the offensive and defensive positions. *B*) Examples of trial sequences. After deciding to move to the left or right (Decision), participants watched a video of the outcome (Encoding). Then, based on a cue (Prompt), participants mentally simulated what just occurred (Remember), what could have occurred (What If), or the thought about the cause of the outcome (Cause) while looking at a blank screen (Simulation). Finally, participants made a judgment about what they just imagined (Judgements).

1B, Decision). They then watched a video of the objects moving to encode the outcome, namely whether the ball scored or the goalie blocked the ball from scoring (Figure 1B, Encoding). Unknown to the participants, score and miss trials occurred randomly and equally often. Participants were instructed to encode the video focused on the ball (offensive position) or the goalie (defensive position). Participants then saw a centrally presented prompt ("Remember", "What if?", or "Cause") for two seconds (Figure 1B, Prompt). This prompt instructed participants to mentally simulate a possibility while looking at a blank screen (Figure 1B, Simulation). If participants saw the prompt "Remember", they were instructed to mentally simulate what actually happened during encoding; if they saw the prompt "What if?", they were instructed to mentally simulate what would have happened had they moved in the other direction; and if they saw the prompt "Cause", they were instructed to mentally simulate how the movement of their object caused the ball to score or miss. Regardless of condition, we encouraged participants to generate a visual mental image.

Finally, participants answered a question about what they just imagined (Remember: "To what extent do you think that the ball scored?"; What if?: "To what extent do you think the ball would have scored if [the ball/the goalie] had moved [left/right]?": Cause: "To what extent did [the ball/the goalie]'s moving [left/right] caused the ball to [score/not score]?"; Figure 1B, Judgments). As an attention check, participants were asked to report the direction that their opponent moved. We excluded all data from trials in which participants failed this check (5% of all trials). All ratings were recorded using an unnumbered, continuous slider scale, with the leftmost end indicating "Not at all" and the rightmost end indicating "Very much."

Participants completed 4 blocks of 12 trials, for a total of 48 trials. All experimental procedures took no more than 60 minutes, including the initial calibration of the eye tracker.

Analysis

Overall, our study had a 2 (position: offensive or defensive) x 2 (display orientation: upward or downward) x 2 (movement: left or right) x 2 (stage: Encoding or Simulation) x 3 (prompt: Remember, What If, or Cause) x 2 (outcome: score or miss) mixed-factors design. Toward simplifying our analytic approach, we collapsed across display orientation and movement by mirroring all trials such that the ball moved upward and to the right resulting in a 2 (position: offensive or defensive) x 2 (stage: Encoding or Simulation) x 3 (prompt: Remember, What If, or Cause) x 2 (outcome: score or miss) design. All fixations were binned using a hexagonal grid that covered the area of videos displayed on the screen.

As our main dependent variable, we analyzed the average number of fixations y_i across the visual field within each trial i using a Poisson distribution with a group-level fixation rate λ_i, estimated on the log scale to ensure a positive fixation rate. We modeled fixation rates as a sum of (a) a global intercept a, (b) a group-level fixation map $f_{c[i]}$, and (c) a participant-level effect $\tilde{f}_{c[i],p[i]}$, where both the group-level and participant-level effects were estimated as Gaussian processes (GPs) using a squared exponential kernel with length-scale ρ and marginal standard deviation α. GPs are a non-parametric Bayesian approach that can estimate non-linear and spatially correlated patterns in data, which makes them ideal for analyzing eye-tracking data (Rasmussen & Williams, 2006). To compare fixation rates between conditions, we used the Savage-Dickey ratio (with significance threshold $BF_{10} > 10$) and 95% credible intervals, (Dickey & Lientz, 1970; Makowski, Ben-Shachar, Chen, & Lüdecke, 2019). For significant clusters, we report the maximum difference within each cluster.

Results

Judgments

First, as a manipulation check, we tested whether participants' behavioral judgments varied across conditions with separate 2 (position: offensive or defensive) x 2 (outcome: miss or score) Bayesian regressions for Remember, What if?, and Cause trials using the package *brms* with participant-level intercepts and used standard normal priors for all coefficients (Bürkner, 2017). In Remember trials, when asked to judge the extent to which the ball scored, there was a significant effect of outcome such that participants accurately reported

$$y_i \sim Poisson(\lambda_i)$$
$$ln(\lambda) = a + f_{c[i]} + \tilde{f}_{c[i],p[i]}$$

$$a \sim \mathcal{N}(0,5)$$

$$f_{c[i]} \sim GP(0, K_{\rho,\alpha})$$
$$\rho \sim InvGamma(10,1000)$$
$$\alpha \sim \mathcal{N}(0,1)$$

$$\tilde{f}_{c[i],p[i]} \sim GP(0, K_{\tilde{\rho},\tilde{\alpha}})$$
$$\tilde{\rho} \sim InvGamma(10,1000)$$
$$\tilde{\alpha} \sim \mathcal{N}(0,1)$$

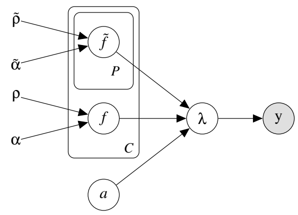

Figure 2: Gaussian process model of fixation rate. Fixation counts y are modeled using a Poisson distribution with rate λ, as a sum of an intercept a, a group-level fixation map f, and a participant-level fixation map $\tilde{f}$.

higher ratings that the ball scored when it actually scored than when it missed (β = .86, 95% *CI* = [.83, .89], *BF* > 4000). There was no effect of position (β = -.01, 95% *CI* = [-.05, .02], *BF* = .02) or interaction between outcome and position (β = .02, 95% *CI* = [-.03, .06], *BF* = .03). These findings indicated that participants correctly identified the actual outcome of the ball on Remember trials.

In What if? trials, when asked to what extent the ball would have scored had the ball (offensive) or goalie (defensive) moved in the other direction, there again was a significant effect of outcome: participants made lower ratings when the ball had scored than when it had missed (β = -.78, 95% *CI* = [-.83, -.73], *BF* > 4000). There was no effect of position (β = .03, 95% *CI* = [-.02, .08], *BF* = .06) or interaction between outcome and position (β = -.01, 95% *CI* = [-.08, .06], *BF* = .04). These findings confirm that participants correctly identified what would have occurred in What if? trials.

In Cause trials, when asked to judge whether their object's movement caused the ball to score or miss, participants reported high causal judgments regardless of outcome and position. That is, there was no effect of outcome (β = .03, 95% *CI* = [.00, .07], *BF* = .10), no effect of position (β = .01, 95% *CI* = [-.08, .1], *BF* = .05), and no interaction (β = .03, 95% *CI* = [-.02, .09], *BF* = .06) on causal judgments.

Eye movements

Encoding Raw fixations made during encoding are presented in Figure 4. At encoding, participants did not know which prompt would follow the stimulus (Remember, What if?, or Cause). As such, we predicted no differences in eye movements between these conditions at encoding. Indeed, there were no significant differences in fixation rate during encoding for defensive participants, and there was only a small difference observed for offensive participants (Figure 5). Specifically, offensive participants were more likely to fixate on the upper-left corner of the stimulus in Cause trials compared to Remember trials when the ball scored (β = 1.62, 95% *CI* = [.04, 3.33], *BF* = 15). This location corresponded with the actual movement of the goalie in these trials. In What if? trials, offensive participants were also less likely to look at this same location than in Remember trials when the ball missed (β = -3.18, 95% *CI* = [-6.65, -.35], *BF* = 47). In these trials, this visual space corresponded with the counterfactual movement of the ball. Notably, though, these differences were relatively small and did not replicate systematically across the conditions.

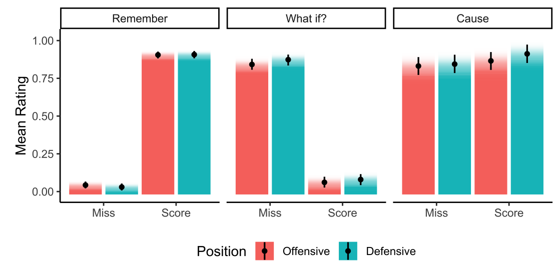

Figure 3: Mean judgments and 95% CIs of whether the ball scored (Remember), whether the ball counterfactually would have scored (What If), and whether moving left/right caused the ball to miss/score (Cause).

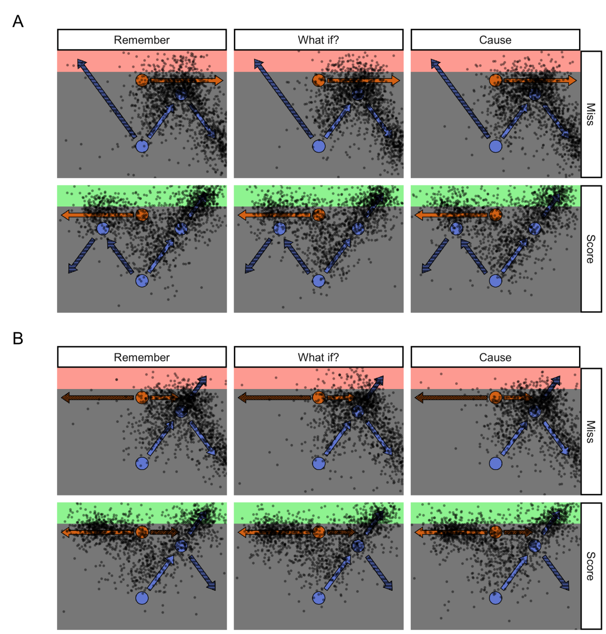

Figure 4: Fixations made during encoding for (*A*) offensive and (*B*) defensive participants. Solid and striped arrows depict the actual and counterfactual movements of the ball and goalie respectively.

Simulation Raw fixations made during simulation are presented in Figure 6. We first compared eye movements across Remember and What if? trials to investigate differences in mental simulations that were unique to counterfactual mental

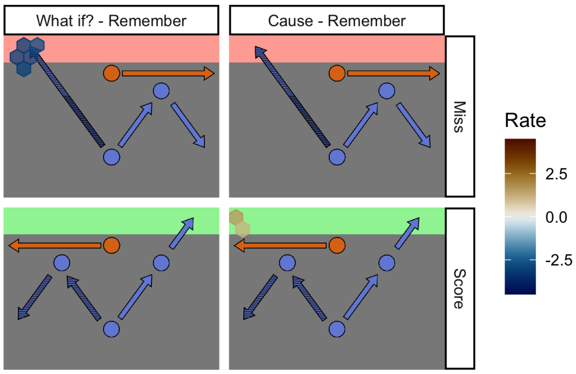

Figure 5: Contrasts of fixation rates during encoding for offensive participants (there were no significant differences for defensive participants). Solid and striped arrows depict the actual and counterfactual movements of the ball and goalie respectively. Brown indicates locations where there were a greater proportion of fixations occurring for What if? or Cause simulations than during Remember simulations.

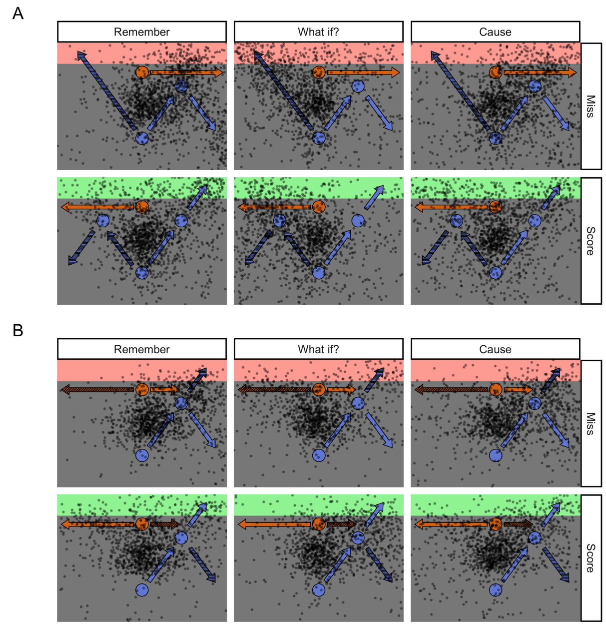

Figure 6: Fixations made during simulation for (*A*) offensive and (*B*) defensive participants. Solid and striped arrows depict the actual and counterfactual movements of the ball and goalie respectively.

simulation. In What if? trials, compared to Remember trials, participants were more likely to fixate to locations where the objects would have counterfactually moved (brown regions in Figure 7). This pattern was observed in offensive participants both when the ball missed (β = 3.93, 95% *CI* = [2.25, 5.83], $BF > 4000$) and when it scored (β = 4.47, 95% *CI* = [2.12, 6.88], $BF > 4000$). This pattern of results was also observed in defensive participants when the ball missed (β = 3.30, 95% *CI* = [1.87, 4.69], $BF > 4000$) and scored (β = 1.73, 95% *CI* = [.39, 3.07], *BF* = 52). Participants were also less likely to look at regions where the objects actually moved when mentally simulating a counterfactual alternative than when mentally simulating what actually happened (blue regions in Figure 7). This pattern held for both offensive participants when the ball missed (β = -2.12, 95% *CI* = [-3.51, -.92], *BF* = 425) and scored (β = -2.44, 95% *CI* = [-3.39, -1.55], $BF > 4000$), as well as for defensive participants when the ball missed (β = -2.77, 95% *CI* = [-4.88, -.72], *BF* = 125) and scored (β = -1.85, 95% *CI* = [-2.84, -.79], *BF* = 426). These results confirm that participants mentally simulated the actual events when asked to remember what just happened, but visually mentally simulated a counterfactual alternative when asked what would have happened in that scenario.

Critically, we next compared eye movements across Cause and Remember trials to determine the sort of mental simulations participants engaged when making causal judgments. For offensive participants, we found a clear pattern: compared to Remember trials, participants in Cause trials were significantly more likely to fixate in regions where the objects would have counterfactually moved regardless of whether the ball had actually missed (β = 2.38, 95% *CI* = [.56, 4.26], *BF* = 83) or scored (β = 3.13, 95% *CI* = [1.38, 4.89], *BF* = 1598). Unlike for counterfactual simulation, there were very few differences across Cause and Remember trials in the tendency to look at locations where the objects had actually previously moved (blue regions in Figure 7). This collective evidence suggests that participants were mentally simulating both what actually happened and what counterfactually would have happened to make causal judgments.

Our observations for defensive participants were less clear. In Cause trials, defensive participants were more likely to look in the lower-left region during simulation than in the Remember trials, both when the ball had missed (β = 2.42, 95% *CI* = [.30, 4.99], *BF* = 32) and when it had scored (β = 1.52, 95% *CI* = [.20, 3.88], *BF* = 26). This suggests that participants were mentally simulating *something* beyond the actual movements of the objects in Cause trials, but we speculate further on this point in the Discussion.

Discussion

There are conflicting views about how people make causal judgments (Dowe, 2000; Salmon, 1997; Wolff, 2007; Mandel, 2003; Hume, 1739; Lewis, 1974; Gerstenberg et al., 2021; Pearl, 2009; Quillien, 2020) and whether visual mental simulation plays a key role in that process (Davis & Marcus, 2015; Kubricht et al., 2017). In the current work, we asked participants to play a ball-shooting game and, while looking at a blank screen, mentally simulate (a) the actual outcome, (b) a counterfactual outcome, or (c) think about the causal relationship between the objects' movements and the outcome. We recorded and compared eye movements across these conditions to investigate how people engage mental simulations when making a causal judgment.

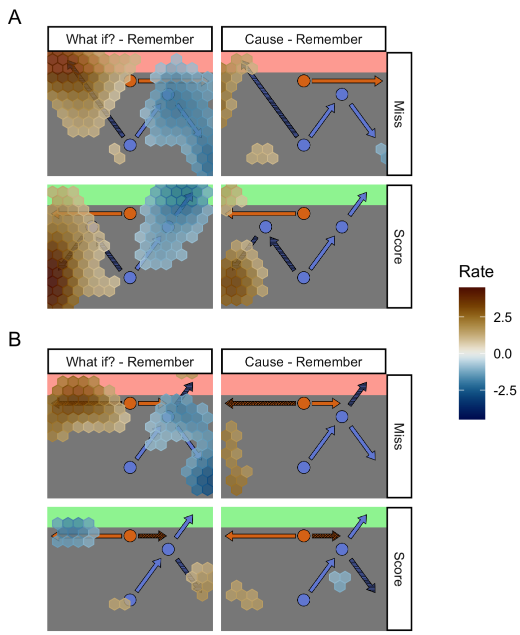

Figure 7: Contrasts of fixation rates during simulation for (*A*) offensive and (*B*) defensive participants. Solid and striped arrows depict the actual and counterfactual movements of the ball and goalie. Brown indicates locations where there were a greater proportion of fixations occurring for What if? or Cause simulations than during Remember simulations.

Our findings showed that participants moved their eyes in patterns consistent with the events that they were mentally simulating. Specifically, when participants mentally simulated what had just happened (*Remember*), they moved their eyes to locations where the objects had just moved. This is consistent with past research showing that when mentally simulating previously encoded objects, people tended to move their eyes to spatial locations once occupied by the remembered objects (e.g., Altmann, 2004; Brandt & Stark, 1997; Richardson & Spivey, 2000), which perhaps facilitates the memory retrieval of the simulated content (e.g., Bochynska & Laeng, 2015; Johansson & Johansson, 2014; Laeng et al., 2014). Our findings further show that when participants mentally simulated counterfactual alternatives (What if?), they moved their eyes to locations where the objects would have counterfactually moved. This demonstrates that—in the absence of ongoing visual input—eye movements could also reflect the contents of counterfactual thoughts, perhaps toward facilitating the recall and recombination of previously encoded sensory details. This also indicates that these retrospective eye movements were not simply reinstated looking patterns from what had actually happened at encoding.

Critical toward adjudicating between process and counterfactual theories of causal judgment, our findings showed that when making a retrospective causal judgment (Cause), participants in the offensive condition looked both to where the ball had actually moved as well as to where it counterfactually could have moved. Thus, our findings suggest that offensive participants were mentally simulating the counterfactual alternative in comparison to what actually happened when retrospectively making a causal judgment. We interpret these eye movements as counterfactual in nature for several reasons. First, our experimental design was such that actual movements, counterfactual movements and future projected movements were spatially dissociated. Second, causal judgments were made after the perceptual information was removed, thus the mental simulations by necessity depicted events in an imagined subjective past. Third, our findings cannot have emerged from differences at encoding, as participants did not know what they would later need to mentally simulate, and our findings showed largely no differences in eye movements across the simulation conditions at encoding. As such, our findings for offensive participants provide strong evidence in favor counterfactual theories of causal reasoning.

While our findings were clear for offensive participants, they have some limitations. Specifically, the pattern of results for defensive participants in Cause trials did not clearly emulate those observed in the What if? trials. That is, in Cause trials compared to Remember trials, we did not see a significant increase in fixations to locations where the objects would have counterfactually moved. While these effects weren't significant, however, they did trend in the predicted direction. Notably, the spatial regions corresponding to counterfactual movements were much smaller in the defensive than offensive position. Moreover, we saw substantial within-participant variability in participants' eye movements during mental simulation overall, possibly due to differences in the vividness of mental imagery between participants (Bone et al., 2019): some participants systematically moved their eyes during mental simulation, while others preferentially looked at the center of the screen. Considering this collectively, we speculate that our effects in the defensive position were insignificant due to insufficient power. Even though the predicted effects were not significant, we did find an unpredicted increase in fixations to the bottom-left region in Cause compared to Remember trials. One possible explanation for this result is that defensive participants were counterfactually manipulating the movement of the ball, either in addition to or instead of the goalie. That said, fixation rates to this region were low overall, and thus this effect might have appeared spuriously as a result of spatial smoothing or simply by chance.

In conclusion, participants moved their eyes in distinct patterns that were consistent with visual mental simulations of counterfactuals while retrospectively making causal judgments. Our findings thus favor counterfactual theories of causal reasoning, showed how retrospective eye movements during mental simulation can reflect this reasoning, and established eye tracking as a novel methodological approach for investigating causal reasoning and counterfactual thinking more broadly.

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