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Human Vision Reconstructs Time to Satisfy Causal Constraints

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Abstract

The goal of perception is to infer the most plausible source of sensory stimulation. Unisensory perception of temporal order, however, appears to require no inference, because the order of events can be uniquely determined from the order in which sensory signals arrive. Here, we demonstrate a novel perceptual illusion that casts doubt on this intuition: In three experiments (N = 607), the experienced event timings were determined by causality in real time. Adult participants viewed a simple three-item sequence, ACB, which is typically remembered as ABC in line with principles of causality. When asked to indicate the time at which events B and C occurred, participants' points of subjective simultaneity shifted so that the assumed cause B appeared earlier and the assumed effect C later, despite participants' full attention and repeated viewings. This first demonstration of causality reversing perceived temporal order cannot be explained by postperceptual distortion, lapsed attention, or saccades.

Keywords

perception, causality, time, temporal order, open data, open materials, preregistered

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Imagine your friend coming toward you holding a nice cup of tea. But her hands are wet, and the cup slips, beginning its free fall. Even more unexpectedly, the cup shatters just before hitting the ground. Do you think that you would spot such a weird succession of events? Previous research indicates that you probably would not (Bechlivanidis & Lagnado, 2013, 2016; Tecwyn et al., 2020). Well, maybe you were not paying attention, or perhaps the scene was too weird to be remembered accurately. Now imagine that the same scene is repeated again and again in front of your eyes, and you are asked to focus on the shattering and pinpoint the exact time when it happens. Do you think you would fare any better? Is our perception of time and temporal order a faithful reflection of what happens in the world (or at least what arrives at our retinas), or can seemingly higher-level expectations, such as causality, affect the order in which we experience events occurring?

Past research shows that judgments of temporal order are not always accurate. In the prior-entry effect (Titchener, 1908), attended events appear earlier because of privileged processing. Perhaps similarly, differences in luminance and contrast (Holcombe, 2015) affect the perceived order of events. In multisensory integration (Stein & Meredith, 1993), temporally separated stimulation is integrated to form unified and coherent percepts. When the timing of stimulus presentations is manipulated to occur closely before and after saccadic eye movements, their order is reversed (Kresevic et al., 2016; Morrone et al., 2005). More relevant to the current purposes, it has been shown that

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when presented with stimuli that give the impression of a recently learned (Bechlivanidis & Lagnado, 2013) or a familiar (Bechlivanidis & Lagnado, 2016) causal relationship that nevertheless violates the expected temporal order, adults and children as young as 4 years old (Tecwyn et al., 2020) report having seen the causal instead of the objective temporal order of events.

These prior demonstrations of order reversals, however (see Holcombe, 2015, for an extensive review), depend on split attention, stimuli that change between saccades, or integration of multimodal signals and are usually revealed in post hoc reports that are subject to memory distortions. Therefore, under conditions of unconstrained attention to uniform unisensory stimuli, one would still intuit that, at the time of perception, the order of experiences will match the order of events in the world. In other words, provided that people attend closely to the events in question and use the same sensory modality, and provided that there is no interval between their experience and its report, the perceived order will coincide with the order in which stimuli arrive at their sensory organs. Although this describes what we take to be an intuitive view, there are indeed theoretical accounts of experience, such as the *brain-time theory* (Dennett & Kinsbourne, 1992; Holcombe, 2015) or the *mirroring theory* (Mellor, 1985; Phillips, 2014), that assume such a direct mapping between the temporal structure of reality and of experience. What underlies this intuition is that, whereas spatial perception, for instance, requires an inferential step to generate 3D percepts from retinal input, temporal-order perception at its most basic does not require any inferential processes at all, because the perceptual input is itself temporally ordered. In other words, internal representations of temporal order—unless they involve cross-modal integration, switches in attention, or substantial differences between stimuli—match the order of experienced external events.

Here, we tested this mirroring intuition by asking whether causality, which also carries temporal-order information (because causes precede their effects), can affect the order in which events are perceived in real time. We modified a paradigmatic Michottean (Michotte, 1963) causal sequence (two objects colliding) by adding a third object to produce a domino-effect collision involving three objects, A, B, and C. Critically, instead of the canonical order ABC (A collides with B, which then collides with C), we presented a reordered version of the sequence: A moves first, but at the time of its making contact with B, C starts moving, and B starts moving only 150 ms later than that (i.e., ACB; see Fig. 1). Earlier research has demonstrated that this stimulus reliably leads people to (a) report that A was the cause of B and B the cause of C and (b) remember having seen ABC instead of ACB (Bechlivanidis & Lagnado, 2016; Tecwyn et al., 2020). This is because, despite the objective ACB order, the event sequence best fits a causal schema ABC, in which B is the presumed cause of C's motion, and thus B must have occurred before its supposed effect C. Until now, such distortions have been demonstrated only at the retrieval stage and have been explained via the constructive nature of memory (Pedro, 2020; White, 2015).

To examine the possibility of the alternative and more surprising perceptual explanation, rather than asking

Statement of Relevance

There are two sources of information on the temporal order of events: the order in which we experience them and their causal relationships, because causes precede their effects. Intuitively, direct experience of order is far more dependable than causal inference. Here, we showed participants events that looked like collisions, but the collided-on object started moving before the collision occurred. Surprisingly, participants indicated in real time that they saw events happening significantly earlier or later than they actually did, at timings compatible with causal interpretations (as if there were indeed a collision). This is evidence that perceived order is not the passive registration of the sequence of signals arriving at the observer but an active interpretation informed by rich assumptions.

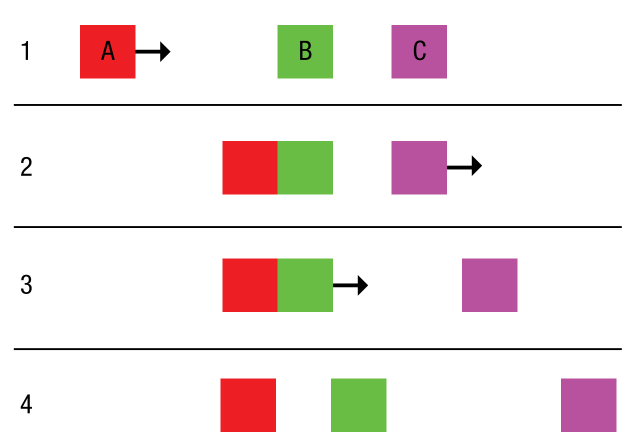

Fig. 1. The reordered Michottean domino-like sequence (the arrows represent the time of motion onset) used in the present experiments. Although the sequence appears to be a series of collisions (in which object A collides with object B, which then collides with object C), object C in fact moves before its presumed cause.

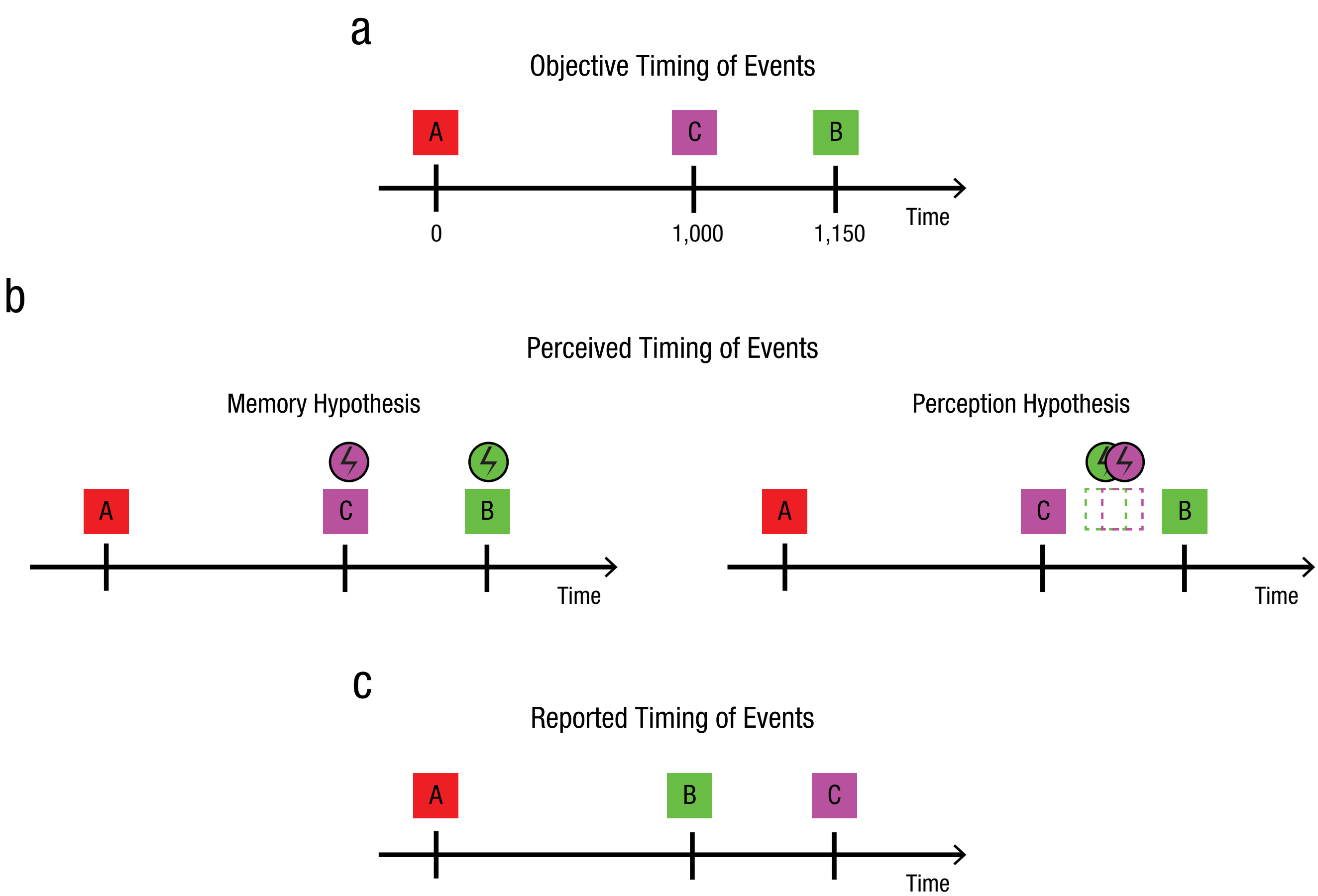

Fig. 2. Memory distortion versus perceptual shifts as underlying mechanisms of temporal causal reordering. Given that previous research indicates that the objective ACB order (a) diverges from the reported ABC order (c), the question is whether this reordering occurs already at the time of perception or whether an initially accurate perception is distorted at a later stage (e.g., during retrieval). In the latter case, participants would be able to accurately synchronize an on-screen flash with the actual motion onsets of B and C (b, left). If order perception is already distorted, however, participants will perceive B moving earlier and/or C moving later, and that would be reflected in the chosen temporal locations of the flash (b, right). Although the absolute size of any temporal shift is not critical, note that the total temporal displacement required to turn a noncausal ACB sequence into the causal ABC sequence is 150 ms, because that is the time that elapses in the former sequence between when C starts moving and when B does.

for judgments of order (which necessarily take place after the fact), we asked participants to indicate in real time when they saw the objects move. If reordering occurs during retrieval, the subjective timings should be accurate. If, however, the effect is already present during encoding, then to turn a noncausal ACB sequence into the causally consistent ABC, object B will be perceived as moving earlier than it does, object C will be seen as moving later, or both (Fig. 2).

Overview of Experiments

In all experiments, participants saw variations of the animation depicted in Figure 1 and had to synchronize a nonlocalized on-screen flash with the motion onset of B or C. To that end, they were given unlimited attempts to adjust the timing of the flash via a slider; each adjustment caused the clip to be played again using the updated flash timing. Our dependent variable was the *point of subjective simultaneity* (PSS), the temporal distance between motion onset of the target object and the final adjusted flash location. The critical clip was invariably the ACB sequence (Fig. 3, top right)—that is, the clip in which the temporal order did not match the apparent causal order of events. Rather than focusing on the absolute PSS, though, we were interested in comparing the PSS in the ACB clip with the PSS derived from clips in which there was no tension between the temporal and causal order, either because by removing one of the objects, we also removed the appearance of any obvious causal relationship (Experiment 1) or because the causal relation was congruent with the temporal order (Experiments 2 and 3).

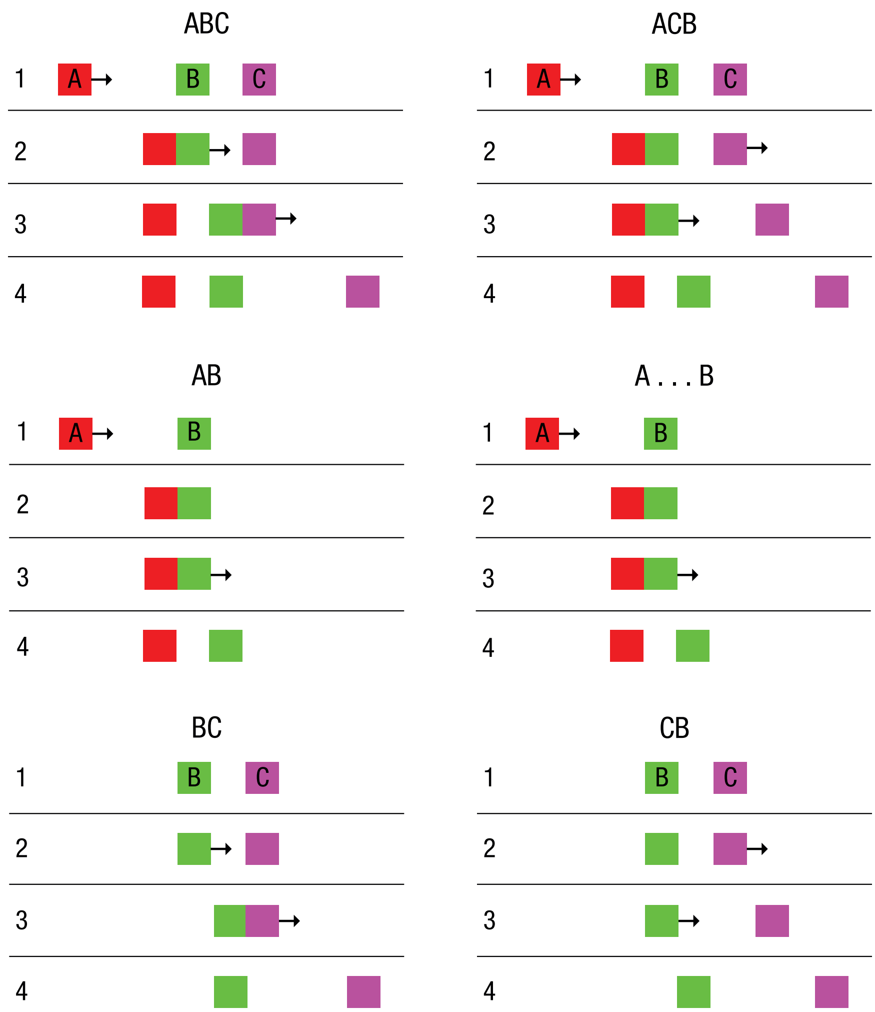

Fig. 3. Target clips shown in the three experiments. In the left column, the order of events follows the causal direction. In the right column, object B starts moving with a delay (150 ms) and after its presumed effect C (if present) has moved. In each column, the sequences shown in the middle and at the bottom are identical to the sequence shown at the top, except that a single object (A or C) has been removed. The clips in the right column were used in Experiment 1, the clips shown in the top and middle rows were used in Experiment 2, and the clips shown in the top and bottom rows were used in Experiment 3.

Experiment 1

Method

Participants. We recruited 280 participants through Amazon Mechanical Turk. The sample size was decided through a power analysis based on earlier pilot studies (power: 80%, α = .05). Following the preregistration plan, we did not include participants in the analysis who reported a PSS exceeding 400 ms in any direction (i.e., abs(PSS) > 400) in any of the nontarget clips or a PSS higher than 1,000 ms in the target clips. Eighty participants were removed on the basis of the first criterion, and none were removed on the basis of the second. The final sample size consisted of 200 participants (mean age = 34.5 years, *SD* = 10.7; 99 females) who received $0.20 for participating and an additional $0.30 if they passed the exclusion criteria.

Materials and design. The experiment was approved by the University College London Research Ethics Committee (EP/2017/005), was preregistered at https://osf.io/w2qd4/, and can be viewed at https://www.ucl.ac.uk/lagnado-lab/experiments/christos/constructing_time/. It was conducted within participants, with each participant seeing eight clips, four of which were nontarget clips and acted as attention checks (see exclusion criteria below). All target clips followed the ACB order (Fig. 3, top right) and differed in the number of objects present (two or three) and in the object with which participants were asked to synchronize the flash (B or C). The two-object clips (A . . . B and CB) were included for comparison with the critical ACB clip because they preserved the same temporal dynamics without implying a causal relationship. Therefore, the four target stimuli were ACB (synced with B), A . . . B (synced with B), ACB (synced with C), and CB (synced with C), as shown in Figure 3 (right column). This resulted in a 2 × 2 within-subjects design with the factors number of objects (three vs. two) and synchronization target (object B vs. object C). The order of clip presentation was randomized per participant, but the alternation between nontarget and target clips was kept constant, starting with a nontarget clip and then alternating between target and nontarget clips.

All clips featured two or three red (hexadecimal color code: No. FF0000), green (No. 00FF00), and purple (No. EC00F0) squares (30 × 30 pixels). The colors were randomly assigned in each clip, but the color of the sync target was kept constant for each participant. The squares moved at a constant speed of 0.2 pixels per frame, and the target frame rate was set at 60 frames per second. The two-object versions of the clips were identical to the three-object ones, except that a single object was invisible: When the sync target was B, object C was invisible, but when participants were asked to synchronize the flash with object C, object A was invisible.[1]

The squares (two or three) were arranged in a row, 150 pixels from the top of the viewport (the user's visible area of a Web page in the browser), and moved horizontally in the same direction either to the left or to the right, randomly decided for each participant. (In what follows, we will describe only the left-to-right versions, because in the right-to-left direction, clips were mirrored horizontally but were otherwise identical.) Square A was positioned 160 pixels from the left edge of the screen. Square B was placed 200 pixels to the right of square A, and square C was placed 30 pixels to the right of square B. There was an initial period of no motion, randomly determined for each clip (1,500–3,400 ms). This was especially important because if the start time were fixed, the correct flash location would be identical between clips, possibly allowing transfer between trials and leading to order effects. When the clip started, square A traveled for 1,000 ms at 0.2 pixels per frame, stopping directly adjacent to square B. Critically, the next object to move was square C; B moved 150 ms later. Object B traveled for 30 pixels and object C for 200 pixels, both at 0.2 pixels per frame. The two-object target clips were, as discussed, identical to three-object ones with one of the squares being invisible. Thus, the A . . . B clip (Fig. 3, middle right) was the same as the ACB clip without square C, whereas the CB clip (Fig. 3, bottom right) was the same as the ACB clip without object A.

The nontarget clips featured two or three squares arranged in a vertical column with a 30-pixel gap between them (equal to the height of each square). When the animation started, the squares moved horizontally in the same direction (to the left or to the right, randomly decided per participant) at 0.2 pixels per frame and came to a halt 200 pixels later. The order of motion onset was randomly determined per clip, but the relative timings were identical to those of the target clips (0 ms, 1,000 ms, and 1,150 ms).

At some point during the animation of each target or nontarget clip, the whole viewport would flash black—that is, the background color was set to black (No. 000000) for a single frame and back to white (No. FFFFFF) again. The initial temporal position of the flash was randomly determined per participant to be either at the beginning of the clip (before any of the squares moved) or at the end (after all squares had reached their final location).

Below the clip, some of the instructions were repeated to participants (task and sync target, unrestricted number of attempts, performance-based fee), and below that there was a slider ranging from 0 to 4,000 ms (the actual values were not visible to participants, but the slider was labeled "earlier" on its left edge and "later" on its right edge). The position of the slider controlled the temporal position of the flash. Its initial position corresponded to the initial temporal location of the flash (extreme left = flash at 0 ms, i.e., flash before animation; extreme right = flash at 4,000 ms, i.e., flash after animation).

Procedure. After providing informed consent, participants were asked for basic demographic information (age, gender) and were introduced to the task: They watched eight clips featuring moving squares. At some point during the animation, the screen flashed black. A slider below the clip allowed them to adjust the temporal position of the flash. Their task was to adjust the flash position so that it occurred exactly when one of the squares started moving (the actual color of the square was mentioned but differed between participants). After each adjustment, the clip would be replayed. There was no limit in the number of adjustments allowed. Finally, it was explained to participants that their fee would depend on their performance in the task.

Participants then watched the eight clips and, for each one, used the slider to adjust the temporal location of the flash. After each clip, participants were reminded that the task would remain the same for the next clip and that they had as many attempts as needed. After the eight clips, participants were asked for any additional comment, were informed about their final fee, and were thanked for participating.

Results

To reach the PSS, participants made an average of 7.9 (SD = 6.03) adjustments of the flash location per clip and thus watched each sequence as many times.[2] As

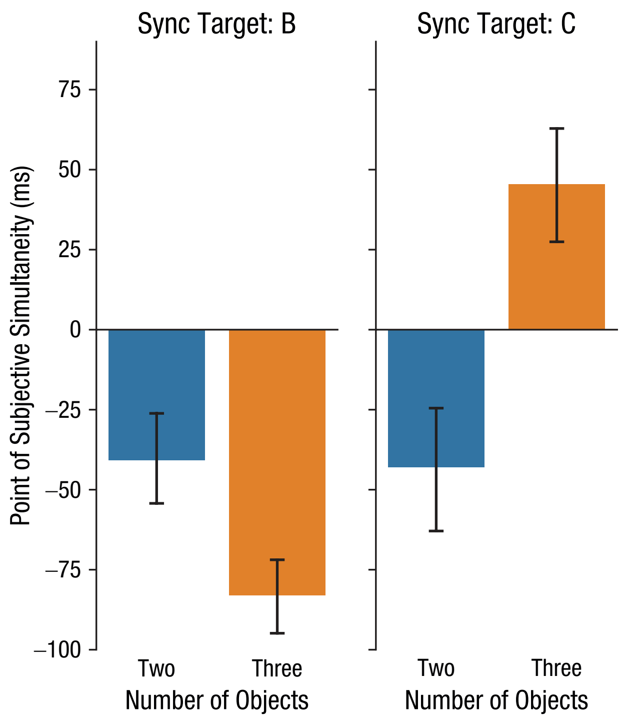

Fig. 4. Average point of subjective simultaneity per clip and synchronization target in three-object ACB and two-object A . . . B and CB sequences in Experiment 1. Error bars represent 95% confidence intervals.

can be seen in Figure 4, when presented with the ACB sequence and asked to indicate when object B started moving, participants positioned the flash on average 82.96 ms (*SD* = 83.01) before the actual movement, and when asked to indicate when object C started its motion, they positioned the flash on average 45.41 ms (*SD* = 128.07) after C actually moved. The figure also shows a clear difference in the PSS between clips in which all objects were visible (orange bars) and clips in which one of the objects was removed (blue bars) and thus causal impressions were weakened or not present at all (Michotte, 1963).

A repeated measures analysis of variance (ANOVA)[3] revealed significant main effects of the factors number of objects (i.e., three vs. two), $F(1, 199) = 10.014$, $p = .002$, $\eta^2 = .048$, and synchronization target, $F(1, 199) = 67.403$, $p < .001$, $\eta^2 = .253$, and a significant interaction effect, $F(1, 199) = 76.348$, $p < .001$, $\eta^2 = .277$. When the flash was synchronized with the onset of object B's motion, the PSS was significantly lower when three objects were present ($M = -82.96$ ms, $SD = 83.01$) than when two objects were present ($M = -40.84$ ms, $SD = 93.59$), $t(199) = 5.392$, $p < .001$, $d = 0.476$. When the flash was synchronized with object C, the PSS was significantly higher in the three-object clips ($M = 45.41$ ms, $SD = 128.07$) compared with the two-object clips ($M = -43.03$ ms, $SD = 139.43$), $t(199) = 7.042$, $p < .001$, $d = 0.661$.

For each participant, we calculated the total temporal displacement by subtracting the PSS when syncing the flash with B from the PSS when syncing the flash with C and compared it with the objectively correct 0 ms and the minimum 150-ms total deviation required for a causally plausible sequence. (Note that earlier perception of motion onset in B translates into a negative PSS, hence the need to subtract.) As shown in Figure 5, for the three-object ACB clip, the total deviation ($M = 128.36$ ms, $SD = 138.51$) differed strongly from 0, $t(199) = 13.246$, $p < .001$, $d = 0.927$, but less so compared with 150, $t(199) = 2.210$, $p = .028$, $d = 0.156$. In contrast, for the two-object clips (A . . . B and BC) the total deviation ($M = -2.19$ ms, $SD = 163.58$) was not significantly different from 0, $t(199) = -0.189$, $p = .850$, $d = 0.013$, but was clearly lower than 150 ms, $t(199) = 3.157$, $p = .0018$, $d = 0.930$. The total PSS in three-object clips was significantly higher than the total PSS in two-object clips, $t(199) = 8.738$, $p < .001$, $d = 0.861$. Finally, a McNemar test comparing the percentage of participants whose total deviation exceeded 150 ms in the three-object clip (45.5%) and the two-object clip (13.5%) was also significant, $\chi^2(1, N = 200) = 91.0$, $p < .001$.

Discussion

The results support the perceptual basis of the effect. When watching the reordered ACB sequence, participants actually perceived B happening earlier and C happening later, at timings that, in total, approach the temporal displacement necessary to turn the ACB sequence into the causal ABC one. Displacements of such magnitude were not observed when one of the objects was hidden. It is thus the illusory causal context that produced the online reversal of temporal order: The insertion of C into A . . . B to produce ACB shifted perception of B earlier in time to yield a causally meaningful ABC percept, whereas the addition of A to CB (to also produce ACB) pushed perception of C later in time to yield the ABC percept.

It may be argued that the difference between the three-object sequence and its two-object counterpart lies not only in the resulting causal impressions but also in varying perceptual loads. If participants attempt to keep track of all objects present, an extra object might increase perceptual load, which may explain the observed inaccuracies. Experiments 2 and 3 compared performance in the ACB clip with a three-object ABC sequence in which the causal and temporal orders coincided and thus no deviations were expected.

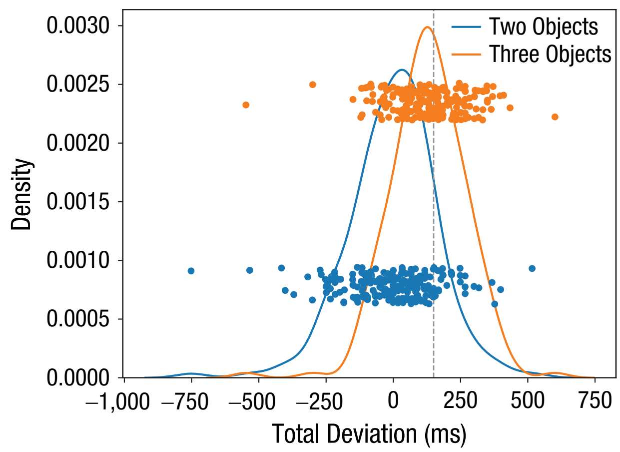

Fig. 5. Total deviation in three- and two-object clips in Experiment 1. Deviation was determined by calculating the total PSS when the flash was synced with B and when synced with C and comparing it with the objectively correct 0 ms and with the minimum 150-ms total deviation required for a causally plausible sequence. The vertical line marks the critical 150 ms, the minimum total shift required to convert the ACB sequence to the causally canonical ABC sequence. Dots show individual participant data. The curves were computed through kernel-density estimation (Gaussian kernel, Scott bandwidth).

Experiment 2

Method

Participants. A different sample of 280 participants was recruited through Amazon Mechanical Turk. The exclusion criteria were the same as before, but instead of 400 ms, we used a stricter threshold of 300 ms (preregistered) for the nontarget clips. As a result, 74 participants were excluded because their absolute PSS was more than 300 ms in at least one of the nontarget clips, and another two participants were excluded because their absolute PSS exceeded 1,000 ms in at least one of the target clips. The resulting sample consisted of 204 participants (mean age = 35.5 years, *SD* = 10.4; 94 females) who received $0.20 for participating and an additional $0.30 if they passed the exclusion criteria.

Materials and design. This experiment was preregistered at https://osf.io/64rjb/ and can be viewed at https://www.ucl.ac.uk/lagnado-lab/experiments/christos/constructing_time/. The design was similar to that of Experiment 1, except that two of the target sequences were replaced by sequences in which the causal and temporal order were congruent, and participants were asked to synchronize the flash only with the onset of object B in all clips. Specifically, to the three-object ACB sequence and its two-object A . . . B counterpart, we added the canonical ABC sequence and the two-object AB sequence that results after removing C (Fig. 3, top left and middle left, respectively). Consequently, the three-object sequences, ACB and ABC, differed only with respect to the object that moved after A stopped, and the two-object sequences differed on whether B moved immediately (AB) or after a 150-ms delay (A . . . B) after A stopped moving. Thus, the design crossed the factors congruency (congruent [i.e., causal = temporal order] vs. incongruent) and number of objects (three vs. two). The nontarget clips and the order of presentation remained the same.

Procedure. The procedure was identical to that of Experiment 1, but this time participants were asked only to synchronize the flash with the onset of movement of object B in all clips.

Results

As before, participants changed the position of the flash and thus watched each clip 7.48 times (*SD* = 5.05) on average. On the left side of Figure 6, we can see that the results closely replicated the findings of Experiment 1. In the ACB clip, participants placed the flash on average 83.97 ms (*SD* = 108.01) before B actually started moving—and in the A . . . B clip, 50.31 ms (*SD* = 118.29) earlier. However, when the temporal order matched the causal order of events (Fig. 6, right), there was actually a small positive offset both when three objects (*M* = 17.63 ms, *SD* = 88.29) and when two objects (*M* = 14.54 ms, *SD* = 67.23) were present.

A repeated measures ANOVA showed significant effects of congruency, $F(1, 203) = 177.103$, $p < .001$, $\eta^2 = .466$; number of objects, $F(1, 203) = 6.029$, $p = .015$, $\eta^2 = .029$; and (critically) their interaction, $F(1, 203) = 6.864$, $p = .009$, $\eta^2 = .033$. Post hoc paired-samples *t* tests showed, as before, a significant difference between the PSS generated from the three-object ACB and the two-object A . . . B clips, $t(203) = 3.049$, $p = .003$, $d = 0.213$, but no significant difference between the three-object ABC clip and its AB counterpart, $t(203) = 0.420$, $p = .675$, $d = 0.029$. Finally, there was a significant difference between the three-object ACB and the three-object ABC clips, $t(203) = 11.52$, $p < .001$, $d = 0.807$.

Discussion

Experiment 2 replicated the significantly negative offset of the perceived temporal location of B when the objective temporal order of events did not follow the causal order. Conversely, when the temporal order was congruent with the causal order, there was a small positive offset. This suggests that it is indeed causality, rather than the number of objects and the associated perceptual

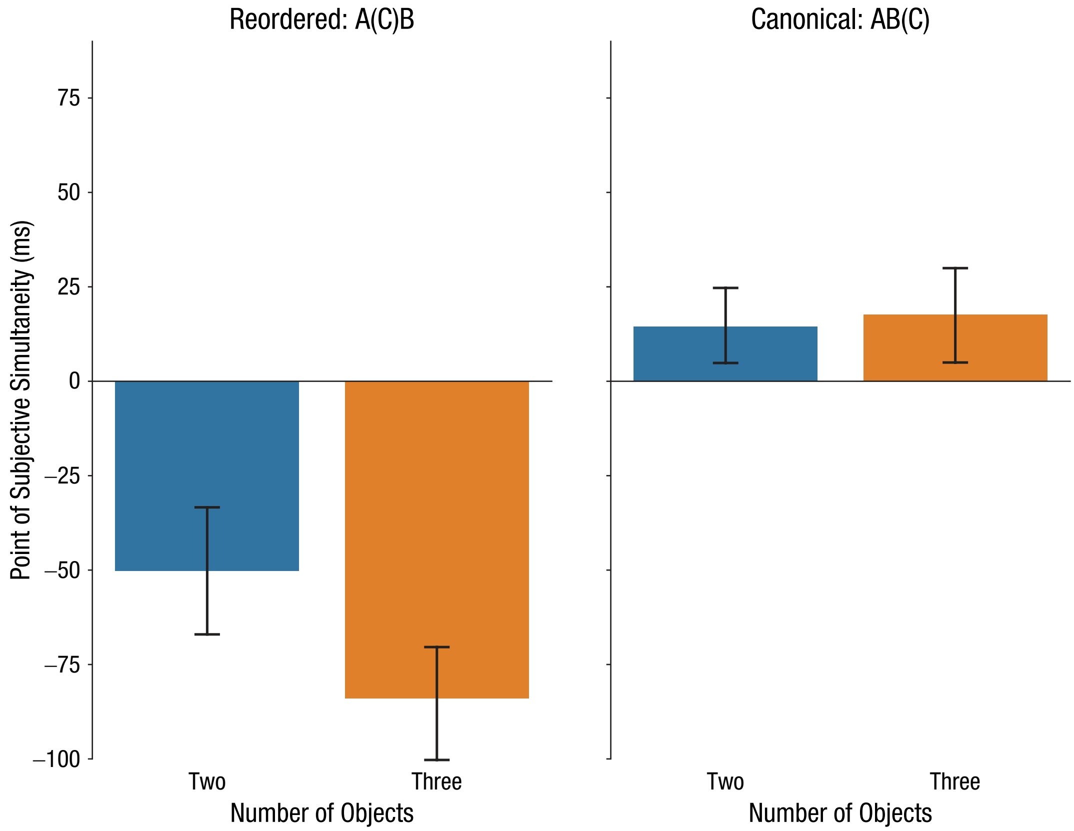

Fig. 6. Average point of subjective simultaneity per clip type (order of events) and number of objects present in Experiment 2 (synchronization was only to object B in this experiment). Error bars represent 95% confidence intervals.

load, that affects the perceived timing of B's onset of motion. In Experiment 3, we followed the same methodology while asking participants to synchronize the flash with the onset of C.

Experiment 3

Method

Participants. We once again recruited 280 participants and applied the same exclusion criteria as in Experiment 2, resulting in the exclusion of 74 participants for deviations exceeding 300 ms in the nontarget clips and three participants for offsets exceeding 1,000 ms in one of the target clips. The resulting sample consisted of 203 participants (mean age = 33.46 years, *SD* = 10.53; 97 female). The participants received the same compensation as before.

Materials and design. This experiment was preregistered at https://osf.io/kcw4v/ and can be viewed at https://www.ucl.ac.uk/lagnado-lab/experiments/christos/constructing_time/. We used the same experimental design as in the first two experiments, but this time we asked participants to synchronize the flash only with the onset of C. To that end, although the three-object clips were the same as in Experiment 2 (reordered ACB and canonical ABC), the two-object clips were modified by rendering object A invisible to generate the CB and BC clips (Fig. 3, bottom right and bottom left, respectively). The design thus, as in Experiment 2, crossed the within-subjects factors congruency (congruent [i.e., causal = temporal order] vs. incongruent) and number of objects (three vs. two).

Procedure. There were no changes in procedure compared with the other two experiments.

Results

Participants required a similar number of 7.85 (*SD* = 5.73) adjustments to reach the PSS for each clip. As shown in Figure 7, we recorded the same effect as in Experiment 1: There was a positive temporal displacement of the onset of C in the reordered ACB clip (*M* = 49.70 ms, *SD* = 106.37). When A was hidden and thus

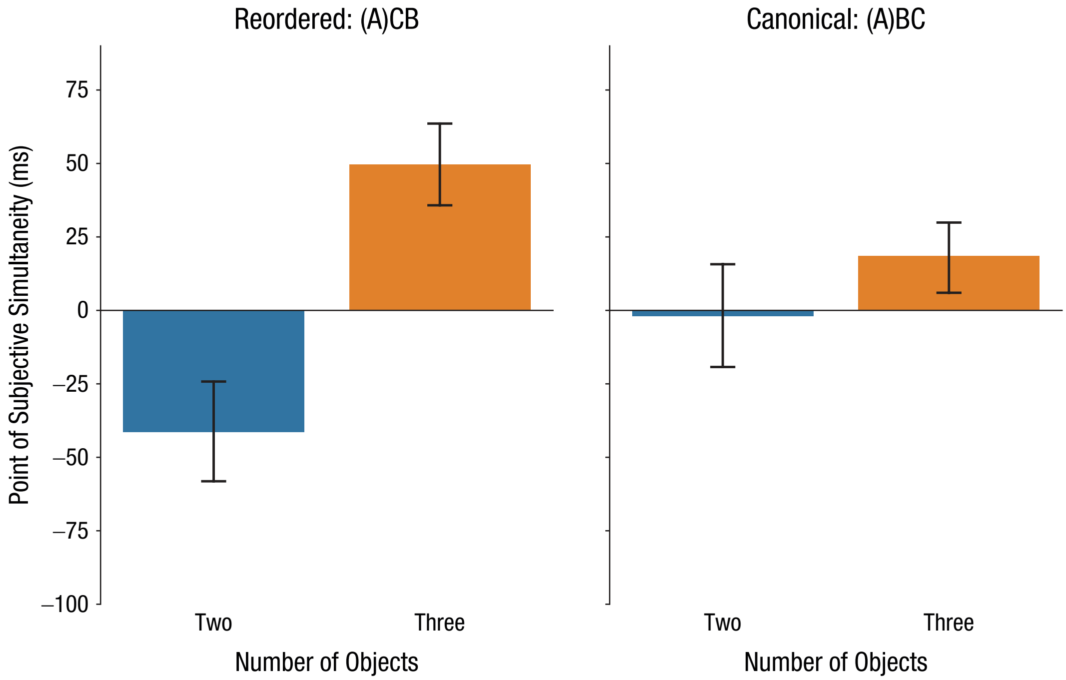

Fig. 7. Average point of subjective simultaneity per clip type (order of events) and number of objects present in Experiment 3 (synchronization was only to object C in this experiment). Error bars represent 95% confidence intervals.

the causal impression was not present, the PSS for C turned negative (M = −41.48 ms, SD = 129.19), as observed earlier. Both the two-object and the three-object canonical clips produced small offsets, negative in the former case (M = −2.03 ms, SD = 124.36) and positive in the latter (M = 18.55 ms, SD = 89.97).

A repeated measures ANOVA showed a significant main effect of the number of objects, $F(1, 202) = 48.130$, $p < .001$, $\eta^2 = .192$, but not of congruency, $F(1, 202) = 0.306$, $p = .581$, $\eta^2 = .002$. Crucially, the interaction was significant, $F(1, 202) = 23.868$, $p < .001$, $\eta^2 = .106$. Planned post hoc t tests showed that the offsets in the ACB clip were significantly higher compared with the offsets both in the CB counterpart, $t(202) = 7.992$, $p < .001$, $d = 0.561$, and in the canonical ABC clip, $t(202) = 3.696$, $p < .001$, $d = 0.259$.

Discussion

Experiment 3 corroborated the findings in Experiments 1 and 2, showing that it is not the number of objects that produces the perceived temporal displacement of events. Only in the presence of a causal expectation or a causal impression, and only when that is incongruent with the objective temporal order of events, does the perceptual system shift the timing of events to match a causal interpretation.

General Discussion

Collectively, our findings constitute the first demonstration of a unisensory perceptual illusion of temporal order induced by causal impressions, indicating that the visual system generates the experienced order through a process of interpretation (Grush, 2016; Holcombe, 2015). Participants were given precise instructions and sufficient time to repeatedly view the sequences, they attended to the critical events using the same modality, and they synchronized object motion with a nonlocalized flash. We can thus confidently rule out alternative explanations based on inattentional blindness, multimodal integration, flash lag, and motion aftereffects. Because stimulus presentation was free and unconstrained relative to the time of saccades, our results cannot be accounted for by transient perisaccadic mislocalization, either (Kresevic et al., 2016; Morrone et al., 2005). Although in this case we examined the effect only with an adult population recruited from a crowdsourcing platform, previous research suggests that children as young as 4 years old are also susceptible to causal reordering, at least when asked to make post hoc reports (Tecwyn et al., 2020). More research needs to be carried out to study the degree of perceptual shift and, more broadly, the generalizability of the current results.

One potential limitation of the work reported here is the possibility[4] that the perceptual signals of temporal order in our stimuli could have been ambiguous (i.e., within the range of a just-noticeable difference [JND]). Specifically, it is possible that when the onset of motion and the flash were less than 100 ms apart, they fell within the same simultaneity window (Holcombe, 2015), and therefore causal impressions were guiding temporal-order judgments in the presence of a completely uninformative temporal signal. We are unaware of any prior research examining JNDs of temporal-order judgments in perceptual-causality stimuli. However, more generally, JNDs in temporal-order judgments tend to be much smaller than the differences we report—for example, from 5 ms (Sweet, 1953) up to 40 ms (Tadin et al., 2010), depending on the nature of the stimuli. One preparation, aimed at deliberately interfering with temporal-order judgments by surrounding each critical target event with 10 extraneous flickering discs, saw JNDs deteriorate as far as 110 ms (Cass & Van der Burg, 2014). Because we observed offsets as large as 80 ms, outside the range of typically observed JNDs, we are reasonably confident that our results go beyond mere cognitive bias. However, the extent to which preceding or subsequent motion of the other objects may have interfered with temporal-order judgment or the extent with which a flashing background may have masked critical events (Nishida & Johnston, 2002; Suchow & Alvarez, 2011) are unknown, and thus we cannot rule out the possibility that causal impressions served as a cognitive factor biasing perceptual responses in light of ambiguous perceptual signals.

It is interesting to note that although our interpretation of the current findings hinges on the presence of causal impressions, and participants in past research have indeed reported such strong impressions (Bechlivanidis & Lagnado, 2016; Tecwyn et al., 2020), the critical ACB sequence is objectively not causal. How can a causal impression strong enough to undermine temporal information be generated from noncausal stimuli? This is a recurring question in the causal-perception literature. The almost universal causal impressions resulting from a prototypical Michottean launching stimulus (Michotte, 1963) are often described as illusions of causality (White, 2006) because the stimulus consists of a highly improbable frictionless, perfectly elastic collision (Runeson, 1983; White, 1988). The explanations offered in that case, and that may also apply to our stimuli, refer either to the similarity of the stimulus with a stored schema (Weir, 1978; White, 2006) or to the inadvertent activation of a low-level causal detector (Michotte, 1963; Scholl & Tremoulet, 2000). Thus, one possibility is that the ACB sequence is, despite its inconsistencies, similar enough to a series of collisions that a causal schema of a domino-like effect remains the most plausible account of what transpired. Alternatively, the speculated low-level causal detector might be activated, because many of the cues to causality (spatiotemporal contiguity, property transmission) are present. The only difference between the causal ABC and the noncausal ACB sequence is that the identity of the object that moves after contact does not match the identity of the object that was interacted on, and this might not suffice to preclude a causal impression.

The influence of causality on time perception is also apparent in multisensory integration (Stein & Meredith, 1993). However, in that case the temporal distortions are usually explained as the attempt of the perceptual system to account for the different transmission media and transduction speeds between, for example, visual and auditory signals with a common source. Our results show that the assumed causal structure of the incoming signals (common cause in multisensory integration or causal chains here) affects the experienced timing of those signals, even in the absence of variable transmission or transduction speeds. A general principle emerges, according to which the relative timing of signal arrival is superseded by inferences regarding the timing of transmission, irrespective of the nature of those signals.

Regarding the process basis of the reordering effect, we discern two possibilities: Based on predictive coding (Hosoya et al., 2005) or integration of sensory evidence with prior experience (Eagleman & Holcombe, 2002), strong causal expectations may overpower the information from the incoming visual signal. Alternatively, if some causal impressions are, as has been argued (Bechlivanidis et al., 2019; Schlottmann, 2000; Scholl & Tremoulet, 2000), the result of low-level perceptual processes, our stimulus was generating two contradictory sensory signals, one due to the objective temporal order and one due to the implied causal order of events, and the latter was weighted more heavily. As in the "checkershadow illusion" (Adelson, 1995), in which color perception is shown to incorporate assumptions about shadows, temporal-order perception is shown here to account for assumptions about causality. And as the recipient of two letters does not rely solely on their order of arrival to infer the order of posting (Dennett & Kinsbourne, 1992), the human visual system uses causation as a postmark to determine the most plausible order of events in the world.

Transparency

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Author Contributions
All the authors conceived the experimental paradigm. C. Bechlivanidis and M. J. Buehner designed the experiments. C. Bechlivanidis analyzed the data. C. Bechlivanidis and

M. J. Buehner wrote the manuscript, and the rest of the authors provided critical input. All authors approved the final manuscript 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.

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Open Practices

All data and analysis code have been made publicly available via OSF and can be accessed at https://osf.io/sz8yt/. The design and analysis plans for the experiments were preregistered on OSF (Experiment 1: https://osf.io/w2qd4/; Experiment 2: https://osf.io/64rjb/; Experiment 3: https://osf.io/kcw4v/). 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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Notes

1. The invisible object in two-object clips was still present in the animation but rendered in the same color as the background (No. FFFFFF). This was done to reduce the possibility of timing variations due to computational load. Both the intended and the actual timings of the events were recorded and showed no systematic variability.
2. The raw data for all experiments can be found at https://osf.io/sz8yt/.
3. In most cases, normality assumptions were violated (Shapiro-Wilk tests), leading us to conduct additional nonparametric equivalents for all tests reported here (e.g., Friedman χ^2 test, Wilcoxon signed-rank test). Given that we did not find any noteworthy differences between the parametric and the nonparametric tests, we opted to report the former, which were preregistered, are arguably robust to normality violations, and are more familiar to readers.
4. We thank one of our reviewers, Alex Holcombe, for suggesting this.

References

Adelson, E. H. (1995). *Checkershadow illusion*. http://persci.mit.edu/gallery/checkershadow

Bechlivanidis, C., & Lagnado, D. A. (2013). Does the "why" tell us the "when"? *Psychological Science*, *24*(8), 1563–1572. https://doi.org/10.1177/0956797613476046

Bechlivanidis, C., & Lagnado, D. A. (2016). Time reordered: Causal perception guides the interpretation of temporal order. *Cognition*, *146*, 58–66. https://doi.org/10.1016/j.cognition.2015.09.001

Bechlivanidis, C., Schlottmann, A., & Lagnado, D. A. (2019). Causation without realism. *Journal of Experimental Psychology: General*, *148*(5), 785–804. https://doi.org/10.1037/xge0000602

Cass, J., & Van der Burg, E. (2014). Remote temporal camouflage: Contextual flicker disrupts perceived visual temporal order. *Vision Research*, *103*(5), 92–100. https://doi.org/10.1016/j.visres.2014.08.008

Dennett, D. C., & Kinsbourne, M. (1992). Time and the observer: The where and when of consciousness in the brain. *Behavioral and Brain Sciences*, *15*, 183–247. https://doi.org/10.1017/S0140525X12000477

Eagleman, D. M., & Holcombe, A. O. (2002). Causality and the perception of time. *Trends in Cognitive Sciences*, *6*(8), 323–325. https://doi.org/10.1016/S1364-6613(02)01945-9

Grush, R. (2016). *On the temporal character of temporal experience, its scale non-invariance, and its small scale structure*. https://philpapers.org/archive/GRUOTT-2.pdf

Holcombe, A. O. (2015). The temporal organization of perception. In J. Wagemans (Ed.), *The Oxford handbook of perceptual organization*. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199686858.013.057

Hosoya, T., Baccus, S. A., & Meister, M. (2005). Dynamic predictive coding by the retina. *Nature*, *436*(7047), 71–77. https://doi.org/10.1038/nature03689

Kresevic, J. L., Marinovic, W., Johnston, A., & Arnold, D. H. (2016). Time order reversals and saccades. *Vision Research*, *125*, 23–29. https://doi.org/10.1016/j.visres.2016.04.005

Mellor, D. H. (1985). *Real time*. Cambridge University Press.

Michotte, A. (1963). *The perception of causality*. Methuen.

Morrone, M. C., Ross, J., & Burr, D. (2005). Saccadic eye movements cause compression of time as well as space. *Nature Neuroscience*, *8*(7), 950–954. https://doi.org/10.1038/nn1488

Nishida, S., & Johnston, A. (2002). Marker correspondence, not processing latency, determines temporal binding of visual attributes. *Current Biology*, *125*(5), 359–368. https://doi.org/10.1016/S0960-9822(02)00698-X

Pedro, T. (2020). Causal beliefs and perception of temporal order. The 'reordering effect.' *Timing & Time Perception*, *8*(2), 137–161. https://doi.org/10.1163/22134468-20191155

Phillips, I. B. (2014). Experience of and in time. *Philosophy Compass*, *9*(2), 131–144. https://doi.org/10.1111/phc3.12107

Runeson, S. (1983). *On visual perception of dynamic events*. Acta Universitatis Upsaliensis: Studia Psychologica Upsaliensia.

Schlottmann, A. (2000). Is perception of causality modular? *Trends in Cognitive Sciences*, *4*(12), 441–442.

Scholl, B. J., & Tremoulet, P. D. (2000). Perceptual causality and animacy. *Trends in Cognitive Sciences*, *4*(8), 299–309. https://doi.org/10.1016/S1364-6613(00)01506-0

Stein, B. E., & Meredith, M. A. (1993). *The merging of the senses*. MIT Press.

Suchow, J. W., & Alvarez, G. A. (2011). Motion silences awareness of visual change. *Current Biology*, *212*(2), 140–143. https://doi.org/10.1016/j.cub.2010.12.019

Sweet, A. L. (1953). Temporal discrimination by the human eye. *The American Journal of Psychology*, *66*(2), 185–198.

Tadin, D., Lappin, J. S., Blake, R., & Glasser, D. M. (2010). High temporal precision for perceiving event offsets. *Vision Research*, *50*(19), 1966–1971.

Tecwyn, E. C., Bechlivanidis, C., Lagnado, D. A., Hoerl, C., Lorimer, S., Blakey, E., McCormack, T., & Buehner, M. J. (2020). Causality influences children's and adults' experience of temporal order. *Developmental Psychology*, *56*(4), 739–755. https://doi.org/10.1037/dev0000889

Titchener, E. B. (1908). *Lectures on the elementary psychology of feeling and attention*. Macmillan.

Weir, S. (1978). The perception of motion: Michotte revisited. *Perception*, *7*(3), 247–260. https://doi.org/10.1068/p070247

White, P. A. (1988). Causal processing: Origins and development. *Psychological Bulletin*, *104*(1), 36–52. https://doi.org/10.1037//0033-2909.104.1.36

White, P. A. (2006). The role of activity in visual impressions of causality. *Acta Psychologica*, *123*(1–2), 166–185. https://doi.org/10.1016/j.actpsy.2006.05.002

White, P. A. (2015). Visual impressions of generative transmission. *Visual Cognition*, *23*, 1168–1204. https://doi.org/10.1080/13506285.2016.1149533