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Amodal causal capture in the tunnel effect

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Abstract. In addition to identifying individual objects in the world, the visual system must also characterize the relationships between objects, for instance when objects occlude one another or cause one another to move. Here we explored the relationship between perceived causality and occlusion. Can one perceive causality in an occluded location? In several experiments, observers judged whether a centrally presented event involved a single object passing behind an occluder, or one object causally launching another (out of view and behind the occluder). With no additional context, the centrally presented event was typically judged as a non-causal pass, even when the occluding and disoccluding objects were different colors—an illusion known as the 'tunnel effect' that results from spatiotemporal continuity. However, when a synchronized context event involved an unambiguous causal launch, participants perceived a causal launch behind the occluder. This percept of an occluded causal interaction could also be driven by grouping and synchrony cues in the absence of any explicitly causal interaction. These results reinforce the hypothesis that causality is an aspect of perception. It is among the interpretations of the world that are independently available to vision when resolving ambiguity, and that the visual system can 'fill in' amodally.

1 Introduction

It is well known that recovering the three-dimensional structure of the world presents the visual system with an inverse problem (Marr 1982). For example, a single dot in a three-dimensional space can project onto a two-dimensional surface in infinite ways, producing insurmountable ambiguity for the visual system. A single dot on the retina could genuinely reflect a single dot, but it could also reflect a row of identical dots aligned in the same horizontal plane. Yet the visual system seldom interprets such an image as a row of dots, seemingly aware of how unlikely it would be for one's viewpoint to align these objects so precisely. In other words, our visual system avoids interpretations of retinal inputs that would assume physical coincidences.

Vision applies coincidence avoidance as a heuristic solution in seemingly all the inverse problems it seeks to solve. Among these problems is object persistence. The visual system must continuously determine whether some stimulation reflects a new object or a new view of a previously seen object. Avoiding coincidences is perhaps the paramount rule employed in making such determinations, manifesting itself in the more specific rule of spatiotemporal priority: if new stimulation appears close enough in time and space to previous stimulation, then vision often assumes a single object as the source of that stimulation (Dawson 1991; Flombaum et al 2010). The challenge of persistence becomes especially difficult when occlusion is involved. Whenever a moving object becomes completely occluded, the visual system will need to decide whether a disoccluding object is the same one that became occluded or a different one. The tunnel effect (figure 1a) provides one simple and robust example of spatiotemporal priority applied under these circumstances. Here, a moving object (eg a red disc) becomes occluded by a foreground surface (the 'tunnel'), and then a visually distinct object (eg a blue disc) emerges at the occluder's opposite end and at the right time and place given the trajectory of the first object. Observers typically perceive a single and persisting

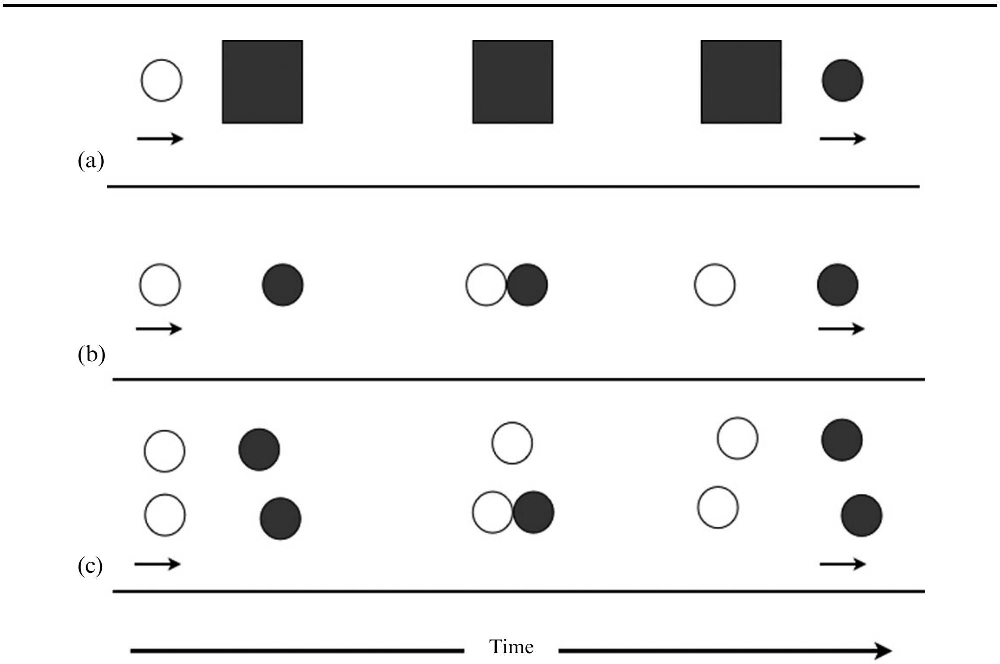

Figure 1. Schematic depictions of three phenomena. In the tunnel effect (a), one object moves behind an occluder and a differently colored object emerges on the other end. With spatiotemporally continuous motion, observers typically perceive a single object. In the perception of causality (b), one disc moves adjacent to another disc at which point it stops moving and the second disc begins to move. Observers typically perceive causality in these displays. In causal capture (c), an unambiguous causal event (bottom) is presented simultaneously nearby an ambiguous overlap event (top), wherein the initially moving object completely overlaps the stationary object before the stationary one begins to move. Although observers typically see these ambiguous events as the motion of a single disc passing over another, the presence of the causal context event induces the perception of causality in the ambiguous event.

object that spontaneously changed its surface properties while occluded. This percept is both visually salient and can have consequences for behaviors such as change detection and foraging (Burke 1952; Flombaum and Scholl 2006; Flombaum et al 2004; Kawachi and Gyoba 2006; Michotte 1946/1963, 1951/1991). Despite the inherent ambiguity of such displays, subjects rarely report seeing an alternative interpretation of one distinct object entering an occluder and a second distinct object emerging.

The perception of causality is a second example of an inverse challenge faced by vision, and one where coincidence avoidance also appears to apply as a central heuristic. While objects in the world do, of course, collide with one another and often cause each other to move, as scores of empiricists have noted, there is no way to know with certainty whether observed events involve physical collisions or the coincidental and spontaneous motion of objects (Berkeley 1709/1975; Hume 1740/2009; Piaget 1955). Nonetheless, in classic demonstrations, observers routinely report the perception of causality when a moving object suddenly stops adjacent to a stationary one, and then the stationary object begins to move (Michotte 1946/1963, 1951/1991; Yela 1952; see Wagemans et al 2006 for a review). It would be a coincidence if these simultaneous events were unrelated and, to avoid such an interpretation, the percept of a causal relationship is imparted to the stimuli by the visual system. It is worth noting that these impressions really are perceptual and do not merely reflect reasoned decisions that subjects make about displays and events (Choi and Scholl 2006; Leslie 1984; Leslie and Keeble 1987; Scholl and Nakayama 2002). Two studies have even found measurable misperceptions of space as a consequence of the perception of causality (Buehner and Humphreys 2010; Scholl and Nakayama 2004) and, in general, the perception of causality is often irresistible and dependent entirely on basic display parameters, evidencing paradigmatic signatures of visual processing.

Indeed, the irresistibility of visual percepts such as the tunnel effect and the perception of causality belie the ambiguity faced by the visual system. Though most stimuli admit multiple interpretations, what we perceive rarely appears ambiguous. Even when certain displays admit two clear interpretations (eg Rubin's face/vase), we only experience one at a time. In the present study, we sought to explore the extent to which the visual system considers multiple interpretations of dynamic displays. In particular, we asked whether stimuli that generally induce the tunnel effect are evaluated as potentially causal. As noted previously, in the tunnel effect at least two plausible inferences are available. What is typically seen is a single object that moves behind an occluder and emerges at the other end having changed its features while occluded. But an additional class of reasonable interpretations involves two objects, one of which becomes occluded and remains so while a second object emerges. Among this class of interpretations is a physical collision: the object that remained occluded may have launched the object that ultimately disoccluded.

The question of primary interest at present is whether a physical collision can be perceived in an occluded location. One reason to think not is that causality is a relatively high-level attribution, and it may require explicit observation of the moments that two objects interact. In other words, certain kinds of inputs pertaining to the interaction may be necessary and, without them, other context may not be capable of exerting any influence. But previous work has shown that spatial and temporal context can influence how the tunnel effect, and amodal stimuli more generally, are interpreted, at least with respect to the completed shapes of partially occluded figures (Wagemans and d'Ydewalle 1988, 1989). Perhaps, then, the right context can exert an influence on stimuli that would otherwise produce the tunnel effect, resulting in a causal percept instead. This would suggest that a causal interpretation is among those typically considered when the visual system interprets any dynamic events.

To address this issue empirically, we made use of a phenomenon known as causal capture (Scholl and Nakayama 2002; figure 1c). In this demonstration, one displayed event involves an object that moves to overlap a second object completely. After their overlap, the (second) previously stationary object begins to move. These events are ambiguous and are less often seen as physical collisions than as a single object that passes over a permanently stationary object. In the causal capture display an unambiguous, nearby, and synchronized collision event leads to the irresistible percept of a causal launch in these otherwise ambiguous (and usually perceived as passing) sequences. In other words, in causal capture a nearby unambiguous collision tips the perception of an ambiguous overlap event towards launching. Note that in the ambiguous sequence two objects are nonetheless observed simultaneously and in close proximity (even overlapping). In the current experiments, we asked whether causal capture can extend its contagion to two objects that are never seen together, and in a situation where the supposed collision would have happened at an occluded location. To do this we asked subjects to make judgments about events that would normally be perceived in terms of the tunnel effect. Nearby these tunnel events we placed context events that in some cases involved the very context events employed by the causal capture experiments of Scholl and Nakayama (2002). Would these causal context events induce a causal percept instead of the usual tunnel effect? Can one perceive causality—a relatively high-level interpretation that involves a structured relationship among objects—at an invisible location?

2 Experiment 1

In experiment 1 we explored how a nearby launching event might influence the perception of an ambiguous occlusion event. Participants were asked to observe simple displays. They were instructed that each display would involve multiple nearby events, but that they should focus their attention on the centrally presented event. After each trial they reported what they saw in the central target event, specifically whether they perceived a causal launch or not. In this experiment, the centrally presented event was in fact identical in almost every trial, and it almost always involved sequences of motion that typically induce the tunnel effect. (There was one control condition, the 'no emerging test disc' condition, that had an importantly different test event, as described below.) Just above these centrally presented events, we presented a variety of synchronous context events (all of which are described below.) The critical context event involved an unambiguous collision, wherein one object moved adjacent to another object and then the second object began to move when the first one stopped. We tested whether these context events influenced the visual system to interpret the occluded events as involving a collision, thereby arresting the perception of the tunnel effect.

Previous work has shown that such context events bias the perception of an ambiguous overlap event. Critically, however, in this previous work the influenced event (ie the ambiguous one) always included two objects explicitly. In contrast, in the current experiment we asked whether causal capture can take place for an event where only a single object is ever seen at once, and where the critical interaction is occluded. In addition to trials with explicit collision events, we included trials with several other kinds of context events designed either as controls, or to extend a potential finding. All the conditions are described extensively in section 2.1 below. Overall, the purpose of this experiment was to ask (i) whether a percept of the tunnel effect could be arrested, even when spatiotemporal continuity is present, and (ii) whether causality can be perceived amodally in an occluded location.

2.1 *Method*

2.1.1 *Participants.* Ten Johns Hopkins University undergraduates participated in exchange for a small monetary compensation. All of them had normal or corrected-to-normal vision. The protocol for this study was approved by the Johns Hopkins University IRB.

2.1.2 *Apparatus and stimuli.* The experiment took place in a dim, sound-proof room. All displays were presented on a Macintosh iMAC computer at a viewing distance of 60 cm such that the display subtended 39.56 deg by 25.35 deg. Every trial began with a framed triangle (1.21 deg on each side) that appeared at the left edge of the screen pointing toward the right edge. The triangle was presented for 500 ms to indicate where the test event would appear. The events displayed in each trial lasted 1.87 s.

Each trial involved two events simultaneously presented (except for the 'no context' condition, described below) on a black background. The test event was always presented centrally, and the context event was always presented 7.30 deg above the test event. Since the test event was the same in every trial we describe it in detail first, and then we elaborate each of the context events.

The test event was identical to the overlap event in Scholl and Nakayama (2002), except for a gray occluder (4.86 deg $\times$ 4.86 deg) presented at the center of the screen, on top of the overlap location. Every trial started with a white disc (2.43 deg diameter) at the left edge of the screen and a red disc (2.43 deg diameter) in the center of the screen, though the red disc was unobservable because it was 'behind' the gray occluder in the foreground. (The gray occluder was present at the start of every trial and remained present throughout.) The white disc then moved toward the center of the screen at a speed of 30.48 deg s^{-1}. When it arrived at the center of the screen, it completely overlapped the red disc, at which point it stopped moving, and the red disc began to move to the right at a speed of 30.48 deg s^{-1}, eventually emerging from the occluder's rightmost edge, and then finally coming to a stop at the rightmost edge of the display. Again, although it took place, the overlap between the two discs was never observable because of the gray occluder in the foreground. In fact, the red and white discs in the test event were never visible simultaneously.

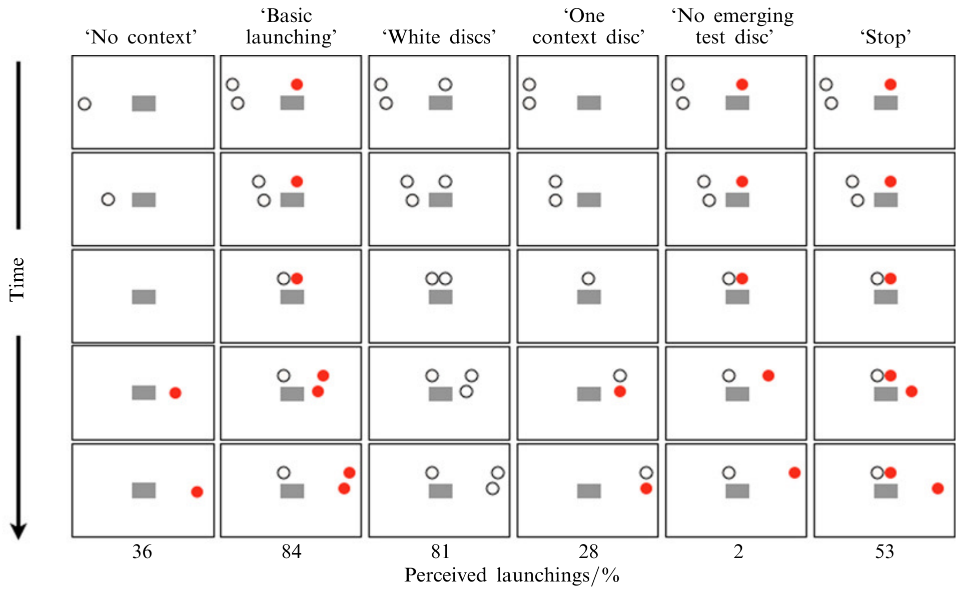

Figure 2. [In colour online, see http://dx.doi.org/10.1068/p6836] Schematic depictions (not to scale) of the conditions in experiment 1, along with the mean percentage of trials reported as involving launches for each condition.

There were 6 different context event conditions. All of these conditions are depicted in figure 2 and described in detail below. The discs in all the context events were the same size as the discs in the test event (2.43 deg diameter). A QuickTime demonstration of these conditions and the conditions for each of the subsequent experiments is available at http://pbs.jhu.edu/research/flombaum/demos/.

(i) *No context condition ('the tunnel effect')*
In this condition no context event was presented near the test event. The test event was presented, as described above, and exactly as it appeared in every condition of this experiment. This condition supplied a baseline. The main question of interest was whether context events could modulate what was perceived in the test event.

(ii) *Basic launching condition*
In this condition, an unambiguous launching event was presented above the test event. In the context event, a white disc was present at the leftmost edge of the display at the start of the trial. There was also a red disc present in the center of the screen, but aligned to the rightmost edge of the test event gray box (which was below). The white disc moved toward the red disc until they became adjacent to one another, at which point the white disc stopped moving and the red disc instantly began moving toward the right edge of the screen at the same speed (30.48 deg s^{-1}). The motions in the context event and test event were completely synchronized, such that a test-event white disc was completely occluded at the same moment that the two objects in the context event were adjacent. This condition supplied the main test of our question. Could the launching context alter what was perceived in the test event?

(iii) *White discs condition*
This condition was identical to the 'basic launching' condition (ii) except for the fact that all the discs in the display, including both discs in the test event, were white. As discussed in section 2.2, this condition was designed to explore the role of surface properties in modulating any contagion from a context event.

(iv) *One context disc condition*
This condition was identical to the 'basic launching condition' (ii) except that the context event included only a single continuously moving white disc that traversed the entire display. The motion of this white disc was synchronized with that of the test event. This condition was included as a control to ensure that not any context event could induce a change in the perception of the test event.

(v) *No emerging test disc condition*
This condition was identical to the 'basic launching' condition (ii) except that no red disc ever emerged from behind the occluder in the test event. This condition was included to ensure that participants did not simply report what they saw in the context event. If they did, then reports to this event should be identical to the 'basic launching' condition.

(vi) *Stop condition*
This condition was identical to the 'basic launching' condition (ii) except that the red disc in the context event never moved. It simply remained stationary at the moment that the white disc came adjacent to it and stopped. This condition was included to ensure that to have an effect, the context event needed to involve a causal collision, not just any kind of interaction between two objects.

2.1.3 *Procedure.* Participants completed 20 trials of each of the 6 conditions, for a total of 120 trials, plus 6 warm-up trials. Each subject observed the trials in a different random order with the only constraint that every group of 12 contiguous trials included two instances of each condition. In each trial, after the dynamic events were presented, a response screen appeared and remained present until a keypress was made.

Participants were instructed to press the 'M' key if they perceived a launch behind the occluder or the 'Z' key if they did not. The exact wording used in the instructions was: "Please press the 'M' key if you think you saw a launch in the test event. Press the 'Z' key if you did not." The instructions also emphasized that subjects should report what they saw, not what they thought about the test events. No elaboration was given with respect to what we meant by a 'launch' in order to discourage participants' over-analysis of the displays and to guide them towards reporting their basic perceptual intuitions. After making a response, participants pressed the space bar to move to the next trial, which started 500 ms later.

2.2 *Results and discussion*
Figure 2 displays the mean percentage with which each condition was reported to be a launch. A one-way repeated-measures univariate ANOVA confirmed that there was a significant effect of condition ($F_{5,45} = 17.67$, $p < 0.001$). Of course, the critical questions in this experiment demand pairwise comparisons among some of the conditions, as well as within-condition comparisons with chance. We discuss these comparisons below in terms of the various implications of this first experiment. All planned comparisons between the 'no context' condition and other conditions were conducted using a Bonferroni adjusted α of 0.008.

2.2.1 *The tunnel effect.* The 'no context' condition—that is, the condition that would usually induce the tunnel effect—produced reports of launching on 35% of the trials across our subjects. This was higher than expected, and not significantly different from chance (50%) ($t_9 = 1.28$, $p = 0.233$). This might be taken to suggest that the tunnel effect is more ambiguous than previously thought, or that our subjects did not really understand the instructions. However, experiments 2 and 3 replicate all the basic results found here, and in those experiments we found much lower reports of launching for the 'no context' condition. Moreover, this result seems to be primarily driven by two subjects who reported the 'no context' condition as involving a launch 90% of the time.

2.2.2 *Amodal causal capture.* The main result in this experiment is illustrated in the simple comparison between the 'no context' and the 'basic launching' conditions. A paired comparison confirmed that subjects were significantly more likely to report the 'basic launching' condition as involving a launch (in the test event) than the 'no context' condition ($F_{1,45} = 15.42$, $p < 0.001$). The 'basic launching' condition was reported as a launch 84% of the time while the 'no context' condition was reported as a launch 36% of the time.

In addition, it was not the case that participants simply reported a launch in the test event whenever some context event was present. This is clear because the 'one context disc' (28%) condition—where no launch was present in the context event—was reported as a launch significantly less than the 'basic launching' condition ($F_{1,45} = 21.98$, $p < 0.001$). Similarly, the 'no emerging test disc' condition was reported as a launch (2%) significantly less frequently than the 'basic launching' condition ($F_{1,45} = 75.64$, $p < 0.001$), despite the fact that there was an unambiguous launch present in the context event. And the 'stop' condition was also reported as a launch (53%) significantly less frequently than the 'basic launching' condition ($F_{1,45} = 7.95$, $p = 0.0071$).

These basic results are interesting for at least two reasons. First, other investigators have suggested that, given spatiotemporal continuity, the tunnel effect should always be observed (Flombaum et al 2010). But here spatiotemporal continuity was always present in the test event, yet when a launch was present nearby participants did not experience the tunnel effect. This is the first demonstration that the tunnel effect can be extinguished when spatial continuity is present. Second, while we know that we readily make inferences about occluded events, the kind of inference made here is perhaps 'higher-level' than any previously described. Participants did not merely 'fill in' a surface behind an occluder, as in amodal completion, but instead they were induced to report, and seemingly even to perceive, a *causal* interaction at an occluded location, thus inferring the presence of multiple distinct and completely occluded objects. We will return to these issues in section 5.

2.2.3 *Does featural similarity matter?* Motivated by previous pilot testing, we chose to include a condition in this experiment that would allow us to consider the relevance of surface properties (ie color) in percepts of causal capture and the tunnel effect. Specifically we included the 'white discs' condition, which was exactly the same as the 'basic launching' condition except for the fact that *all* the discs in the display were white. Critically then, the disc that became occluded in the test event was featurally identical to the disc that eventually disoccluded, supplying a featural match that might have provided reinforcing evidence in favor of the tunnel effect (ie in favor of a single-object interpretation of the test event). Yet we found that causal capture occurred despite the featural similarities. A planned comparison confirmed that the mean proportion of reported launching for the 'white discs' condition (81%) was significantly different from that of the 'no context' condition (35%) ($F_{1,45} = 14.06$, $p < 0.001$). This comparison suggests that synchrony between the context and test event was prioritized by the visual system relative to the test objects' surface properties. In the 'no context' condition, the two test discs *looked* different from one another, in so far as they had different colors, yet they tended to be perceived as a single individual.

But with a context collision event, two discs that looked identical—seen one at a time—were perceived as two different individuals. Spatiotemporal synchrony trumped featural similarity in the interpretation of these hidden events, reinforcing the general conclusion that surface features are not considered relevant by the visual system when making decisions about persistence (Burt and Sperling 1981; Dawson 1991; Flombaum et al 2010; Navon 1976).

2.2.4 *The mere suggestion of two objects?* One alternative explanation of the main result of these experiments is that participants were more likely to perceive a collision in the test event simply because a context red disc presented above the gray box may have been taken to imply that another red disc existed behind the gray box. To test this possibility, the proportion of causal launches for the 'stop' condition (53%) was compared to chance (50%), but there was no significant difference ($t_9 = 0.262$, $p = 0.799$). This suggests that simply having any context event involving two discs was not enough to induce reports of launching more often than chance.

3 Experiment 2

Experiment 1 evidenced a new phenomenon that we term 'amodal causal capture', wherein an ambiguous dynamic occlusion event is perceived as a causal launch because a nearby and synchronized event involves an unambiguous collision. In experiment 2 we sought to replicate these novel findings while also exploring the rules that mediate amodal causal capture. In the case of causal capture for unoccluded stimuli (Scholl and Nakayama 2002), previous work showed that simple grouping cues, even in the absence of an unambiguous launch, could induce the perception of causality (Choi and Scholl 2004). Here we ask whether such basic grouping cues have the same effects for occluded events. In other words, in the current study we asked a somewhat strange question: can causality be perceived in sequences where the expected raw materials—two objects interacting—are never directly observed anywhere in the display, including in the context events?

3.1 *Method*

3.1.1 *Participants.* Ten Johns Hopkins University undergraduates participated for a small monetary compensation. All of the participants had normal or corrected-to-normal vision.

3.1.2 *Apparatus and stimuli.* The apparatus employed in this experiment was identical to that in experiment 1. The stimuli were also mostly identical, with two important exceptions: (i) the test event in this experiment was slightly different from the test event used previously; (ii) we replaced several of the context conditions used previously with different context conditions. We first discuss the changes made to the test event, before going on to describe the context conditions used in this experiment.

In the previous experiment, the test event that took place behind the occluder was actually an ambiguous overlap event. That is, the white disc that began its trajectory on the left side of the screen perfectly overlapped the occluded red disc before the red disc began to move rightward (while the white disc stopped moving). In the current experiment, the events behind the occluder were actually an unambiguous collision. That is, the white disc stopped moving when it touched the leftmost edge of the red disc, at which point the red disc began moving to the right. The reason for this change was simply to ensure that none of the effects described was due to this small potential difference in the underlying nature of the test event. Critically, when occluded (as they were in both experiments), both kinds of events induce the tunnel effect. Readers can observe this for themselves by watching the demos of the 'no context' condition for each

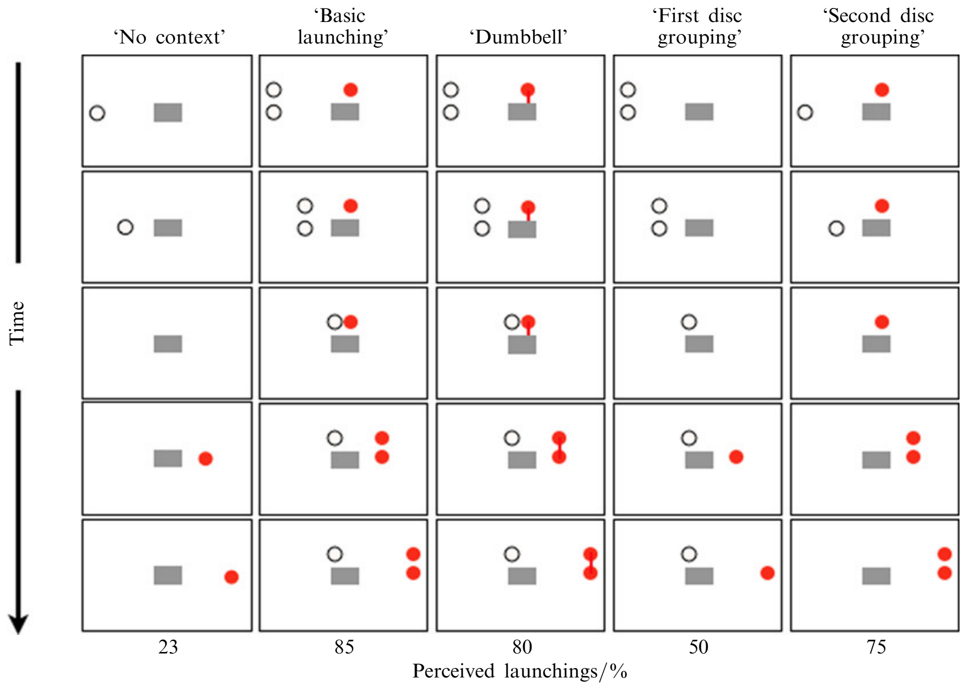

Figure 3. [In colour online] Schematic depictions (not to scale) of the conditions in experiment 2, along with the mean percentage of trials reported as involving launches for each condition.

of the two experiments. Moreover, the data from this and the previous experiment support these perceptual intuitions.

There were five context conditions in this experiment (a schematic of each one is depicted in figure 3):

(i) *No context condition ('the tunnel effect')*
The 'no context' condition was identical to the 'no context' condition in experiment 1, except with respect to the underlying nature of the occluded test event, as described above.

(ii) *Basic launching condition*
The 'basic launching' condition was identical to that in experiment 1.

(iii) *Dumbbell condition*
The 'dumbbell' condition involved no white disc in the context event. Instead, a red disc was present at the start of the trial above the occluder. This red disc was connected via a 0.25 deg red line to the occluded red disc in the test event. When the white disc in the test event touched the red disc in the test event, both red discs began to move rightward together. That the two discs formed a dumbbell was only explicitly observable at the moment that the test event red disc disoccluded. This condition was included to see whether a non-collision context could induce causal capture simply through grouping. This condition included three grouping cues: common motion, color, and connectedness.

(iv) *First disc grouping condition*
This condition was identical to the 'basic launching' condition except that a red context disc was entirely absent from the trial. Thus, a white context disc began the trial at the leftmost edge of the display, and when it arrived above the occluder it simply stopped moving (but remained present in the display). This condition was included to

determine whether grouping cues could induce capture at any stage in the motion sequences, or whether they were only potent for the object that moved as a consequence of the perceived collision.

(v) *Second disc grouping condition*
This condition was identical to the 'dumbbell' condition, except that no red line connected the two red discs. This condition was included to see whether groupings by color and common motion were sufficient to induce amodal causal capture, even without a mechanism for physical contact between the grouped discs.

3.1.3 *Procedure.* The procedure was identical to that in experiment 1, except as follows: participants completed 20 trials of each of the five conditions, for a total of 100 trials, plus 5 warm-up trials. Each subject observed the trials in a different random order with the only constraint that every group of 10 contiguous trials included two instances of each condition.

3.2 *Results and discussion*
Figure 3 displays the mean percentage with which each condition was reported to be a launch. A one-way repeated-measures univariate ANOVA confirmed that there was a significant effect of the context condition ($F_{4,36} = 10.91$, $p < 0.001$). Below we report comparisons between the judgments that we obtained and chance, as well as planned comparisons between the 'no context' condition and the other conditions. All planned comparisons were conducted using a Bonferroni adjusted α of 0.0125.

3.2.1 *The tunnel effect.* A one-sample t-test revealed that the mean perceived launching for the 'no context' condition (23%) was significantly less than chance (50%) ($t_9 = 2.78$, $p = 0.022$). In other words, participants systematically perceived this condition to not involve a collision. As a methodological note, participants did not see a launch here despite the fact that in this experiment, and unlike in experiment 1, what actually took place behind the occluder *was* a collision.

3.2.2 *Amodal causal capture.* Of paramount importance, experiment 2 successfully replicated the basic result of experiment 1. A paired comparison confirmed that subjects were significantly more likely to report the 'basic launching' condition (85%) as a launch compared with the 'no context' condition (23%) ($F_{1,36} = 31.29$, $p < 0.001$). Thus, subjects again experienced amodal causal capture—the perception of a causal interaction in an occluded location.

3.2.3 *Effects of grouping.* The main purpose of experiment 2 was to test the effects of grouping on the amodal causal capture phenomenon. Towards this end we included three conditions that involved only single context discs that could be grouped with one of the test event discs. We found that grouping between the two white discs (ie the initially moving discs) did not induce causal capture in the absence of an explicit collision somewhere in the display. The 'first disc grouping' condition was not reported as a launch significantly more often than the 'no context' condition (50% versus 23%, respectively) ($F_{1,36} = 5.18$, $p < 0.022$). (Note that this is not significant when using a Bonferroni correction.)

However, we found that the 'dumbbell' condition was perceived as a launch significantly more often than the 'no context' condition (80% versus 23%, respectively) ($F_{1,36} = 25.99$, $p < 0.001$), and also that the 'second disc grouping' condition was perceived as a launch significantly more often than the 'no context' condition (75% versus 23%, respectively) ($F_{1,36} = 22.01$, $p < 0.001$). On the basis of these results we can conclude that a context event does not need to involve specifically causal information to produce amodal causal capture. Indeed, these results may be taken to suggest that the 'basic launching' context does not necessarily induce its effects because it includes a collision but, possibly, simply because it supplies grouping cues that link the objects in the context and test events. Thus, this experiment supports a rather surprising conclusion. It demonstrates that physical collisions can be perceived in a display where no collision is ever directly observed, that is, where the inducing context does not involve a collision, and where the perceived collision is inferred to have taken placed entirely out of view. In the 'second disc grouping' condition, causal capture was induced at an occluded location by just a single context disc that neither participated in a collision itself, nor had the capacity to cause the motion of any of the discs in the test event. Yet, because of its grouping by color and common fate with the red disc in the test event, it induced the occluded test event to be seen in causal terms. We return to the implications of this surprising effect in section 5.

4 Experiment 3

Experiment 2 revealed that basic grouping between the test and context events is enough to induce amodal causal capture, even in the absence of any explicitly observable collision. In experiment 3 we further explored the sufficient conditions for the induction of amodal causal capture. Our focus was on two different aspects of the previous set of results. Specifically, we asked whether temporal synchrony might be sufficient to induce the phenomenon. To do this, we included test and context events that moved in the opposite directions from one another, thus extinguishing grouping cues, but leaving temporal synchrony intact. In these conditions, causal collisions still took place in some of the context events at the same time that any inferred causal collision would have taken place in the test event. In addition, we explored the time course of the previously discovered grouping effects by including one condition with an occluder in the context event, so that any grouping would be perceived only after any collisions would have taken place. The relevant context conditions that addressed these issues are described in section 4.1.

4.1 *Method*

4.1.1 *Participants.* Ten Johns Hopkins University undergraduates participated for a small monetary compensation. All participants had normal or corrected-to-normal vision.

4.1.2 *Apparatus and stimuli.* The apparatus and stimuli employed were identical to those in experiment 2, except for the inclusion of three new context conditions as described below. There was a total of five conditions in this experiment, depictions of which can be found in figure 4.

(i) *No context condition*
This condition was identical to the 'no context' condition in experiment 2.

(ii) *Basic launching condition*
This condition was identical to the 'basic launching' condition in experiment 2.

(iii) *Opposite direction condition*
This condition was identical to the 'basic launching' condition, except that the motion direction of the context event was opposite that of the test event. The context discs moved from the right edge to the left edge of the screen while the test discs moved from left to right. This condition was included to determine whether grouping by common fate is necessary for an amodal causal capture, or if temporal synchrony is sufficient.

(iv) *No launcher condition*
This condition was identical to the 'opposite direction' condition, except that it involved only a single red disc that began to move to the left at the moment that the occluded red test disc began to move to the right. This was included as a control condition for comparison with any results that might be found in the 'opposite direction' condition.

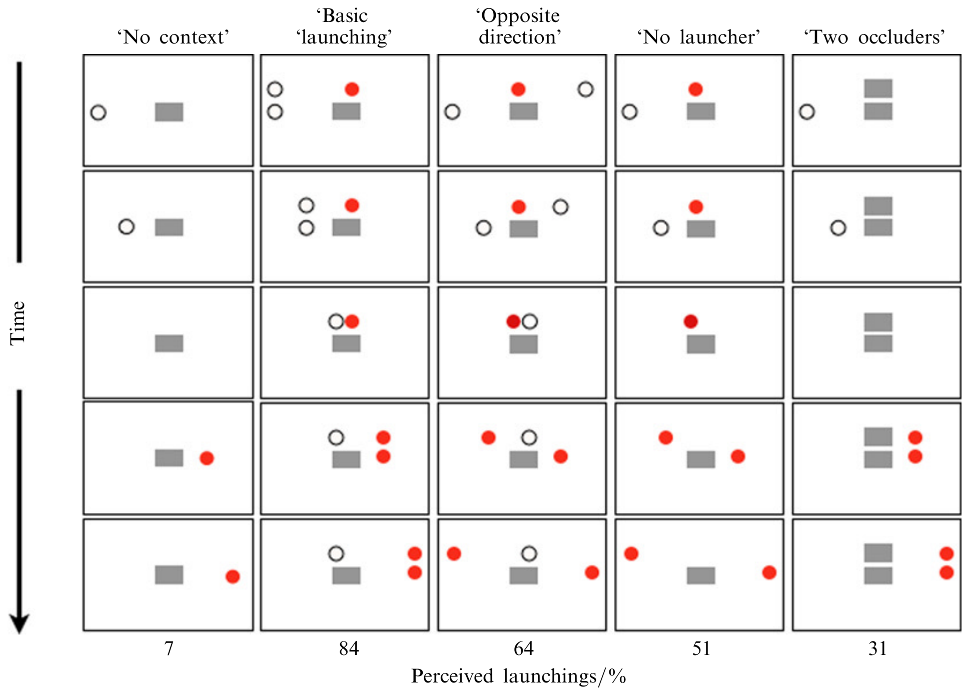

Figure 4. [In colour online] Schematic depictions (not to scale) of the conditions in experiment 3, along with the mean percentage of trials reported as involving launches for each condition.

(v) *Two occluders condition*
This condition was identical to the 'second disc' condition of experiment 2, except that it included a gray occluder hiding the location of the second context disc. The motions of the red context disc and the red test disc were perfectly synchronized, such that they both emerged from their occluders at the same time. The additional gray occluder in the context event was identical to the one in the test event, and the distance between the top of the test occluder and the bottom of the context occluder was 1.54 deg. This condition was included to follow up on the grouping results of the previous experiment. Specifically, we wanted to know whether grouping could have an impact entirely postdictively, in situations where grouping cues were present only a few moments after any collision would have taken place.

4.1.3 *Procedure.* Participants completed 20 trials of each of the five conditions for a total of 100 trials plus 5 warm-up trials. Each subject observed the trials in a different random order with the only constraint that every group of 10 contiguous trials included two instances of each condition.

4.2 *Results and discussion*
Figure 4 displays the mean percentage of perceived launching for each condition. A one-way repeated-measures univariate ANOVA confirmed that there was a significant effect of condition ($F_{4,45} = 8.42$, $p < 0.001$). Below we report comparisons between the judgments that we obtained and chance, as well as planned comparisons between the 'no context' condition and the other conditions. All planned comparisons were conducted using a Bonferroni adjusted α of 0.0125.

4.2.1 *The tunnel effect.* As in experiment 2 the 'no context' condition was reported as a launch significantly less frequently than chance (7%) ($t_9 = 21.98$, $p < 0.001$). This condition was used as a baseline for the planned comparisons.

4.2.2 *Amodal causal capture.* Most importantly, experiment 3 provided a second replication of the main finding of experiment 1, the amodal causal capture phenomenon. The 'basic launching' context was reported as involving a launch significantly more frequently than the baseline 'no context' condition (84% versus 7%, respectively) ($F_{1,45} = 29.85$, $p < 0.001$).

4.2.3 *The strength of grouping.* In this experiment we included one new grouping condition designed to explore how strong a grouping cue must be—and when it must be present—to induce amodal causal perception. In the 'two occluders' condition a red context disc moved in synchrony with, and parallel to the red test disc in the test event. In other words, this condition was identical to the 'second disc' condition in experiment 2, except that an additional occluder was added to the context event. This meant that participants could not group the two discs together until they both emerged from the occluder, which was a few moments after the causal interaction would have taken place. Had this condition induced causal capture nonetheless, it would have illustrated that such effects could be construed entirely postdictively. Unfortunately, the results of this experiment were unclear; participants reported that the 'two occluders' trials involved a launch marginally more often than the baseline 'no context' condition ($F_{1,45} = 4.78$, $p = 0.034$). However, this was still only 31% of the trials, and therefore less than the majority of the time. Future work will have to further explore this condition and the time course of grouping effects in amodal causal capture.

4.2.4 *Synchrony.* The main goal of experiment 3 was to explore the role of synchrony in amodal causal capture. In particular, could amodal causal capture take place when a context event involved a launch, but one that moved in the opposite direction from the events where causality would be induced? We found that synchrony was sufficient to induce the perception of an amodal collision. The 'opposite direction' condition was seen as a launch significantly more often than the 'no context' condition (64% versus 7%) ($F_{1,45} = 16.43$, $p < 0.001$).

Similarly, the 'no launcher' condition was seen as a launch significantly more often than the 'no context' condition (51% versus 7%) ($F_{1,45} = 9.62$, $p = 0.003$). This condition is especially striking since it did not involve either an explicitly visible launch or grouping by common fate. Instead, it simply involved an event (the motion of the red context disc) which commenced in synchrony with the perceived causal launch. This suggests that, overall, the perception of causality may depend primarily on temporal synchrony between events that would otherwise appear unrelated.

5 General discussion

The primary outcome of the present study was the discovery of a new perceptual phenomenon that we have termed 'amodal causal capture'. We presented participants with simple dynamic events that under most circumstances are perceived in terms of the motion of a single and persisting object that changes colors while occluded—an illusion known as the 'tunnel effect' (Burke 1952; Flombaum et al 2004; Flombaum and Scholl 2006). In our displays, however, various nearby context events transformed what was observed behind the occluder such that participants perceived a collision involving two different and simultaneously occluded objects. Previous work has demonstrated such capture effects occurring to ambiguous overlap displays but, critically, displays that involved two objects seen simultaneously (Scholl and Nakayama 2002). We have shown that this contagion can even extend to displays where no two objects are ever observed simultaneously, and where the inferred collision is completely occluded. This amodal causal capture effect is phenomenologically salient (readers can view demonstrations at http://pbs.jhu.edu/research/flombaum/demos/), and in these experiments it was confirmed statistically through comparisons between the 'no context' baseline condition and the 'basic launching' condition (among others). These studies make several theoretical contributions to our understanding of object persistence, amodal visual processing, and the nature of ambiguity in vision.

5.1 *Spatiotemporal priority*
Among the basic challenges faced by the visual system is object persistence. The visual system must continuously determine whether current stimulation reflects new objects, or new views of previously observed objects. That objects often move and occlude one another only complicates the problem. Yet, as with most problems solved by the visual system, we are rarely made aware of the underlying challenge of persistence because our minds come equipped with heuristic solutions that make perception appear seamless, and usually accurate. In the case of persistence, spatiotemporal priority seems to be the rule that usually governs what we see. That is, when objects appear close enough to one another in time and space, they are assumed to be the same regardless of differences in their physical appearances. This rule is applied in the perception of apparent motion, seemingly in how infants and animals construe occlusion events and, of course, in adult perception of dynamic occlusion events, including in the tunnel effect (Baillargeon 1999, 2002; Dawson 1991; Flombaum et al 2004, 2010; Flombaum and Scholl 2006; Navon 1976; Spelke et al 1995; Xu 2002; Xu and Carey 1996). The tunnel effect, in particular, has often been taken as a paradigmatic case of spatiotemporal priority in effect: so long as the kinematics are continuous we see a single persisting object, even when the object changes its surface properties entirely.

The current results cast a shadow on the absoluteness of spatiotemporal priority. In several demonstrations, unrelated context events led to the perception of a collision in displays that possessed kinematic continuity and would have otherwise produced the tunnel effect. (Indeed, the same displays did produce the tunnel effect when no context event was present.) It is worth noting that the percept of amodal causal capture involves a very different interpretation with respect to persistence. Whereas the tunnel effect involves a single persisting object, a collision involves two persisting objects. Accordingly, the current experiments suggest that spatiotemporal priority may not be a complete or exclusive articulation of the rules employed by vision to solve the problem of persistence.

Instead, the current results point to the dominance of a broader principle—coincidence avoidance. Across many different kinds of phenomena, the visual system rejects interpretations that would require a coincidence. Amodal completion is perhaps the best-known example, wherein the visual system assumes a complete surface occluded by another surface, rather than two jagged surfaces that coincidentally align in just the right way. In the current experiments, the visual system similarly can be seen as avoiding coincidences. If the test event did not involve a collision, it would be a coincidence that the test disc moved at exactly the same moment as a nearby collision took place (in the 'basic launching' condition). Given that such a coincidence would be, by definition, unlikely, the visual system seems to favor the interpretation that the test event also involved a causal launch.

Interestingly, we found causal capture even when no explicit launch took place in the context events, a result consistent with previous work on causal capture to ambiguous, but unoccluded overlap events (Choi and Scholl 2004). In experiment 2, for example, 80% of trials were reported as involving a launch when the two red discs were physically connected by a bar, and 75% were reported as launches even when no bar connected the two red discs. Therefore causal capture took place simply because the test and context red discs moved in synchrony, and the effect does not seem to require a specifically causal context event. This surprising effect is consistent with the application of a coincidence-avoiding heuristic, at least broadly construed. If the visual system seeks an interpretation of the events that accounts for the synchronized motion of the red discs, then the red disc that emerges from behind the occluder could not be the same individual as the white disc that originally became occluded. In turn, if the white and red discs in the test event really are different individuals, then they were likely to have collided. It is possible that the white disc even launched both of the simultaneously moving red discs, a very likely interpretation in the dumbbell case, and a reasonable one in the two-disc case since launching at a distance is a known phenomenon (Yela 1952). Though the size of the effect seems to be smaller, the opposite-direction condition that we tested also induced causal capture (64% of the time, and significantly more often than the baseline tunnel event). This was true even when there was no causing object in the test event.

This implies a very general kind of coincidence avoidance, one that is ultimately based on temporal synchrony. When events happen at exactly the same time, the visual system seeks interpretations that account for the coincidence. Importantly, this understanding of coincidence avoidance is not the same as understanding it in terms of spatiotemporal priority. Indeed, it deemphasizes the spatial nature of the heuristic, explaining phenomena entirely in terms of temporal considerations. Consistent with this view, previous work has suggested that the attempt to reconcile temporally synchronized events extends crossmodally. A brief sound at the critical moment can bias the perception of passing events towards collision events (Watanabe and Shimojo 2001). Across all three current experiments, the temporally synchronized movement of unrelated discs biased perception of the test event away from the tunnel effect towards a collision. Spatiotemporal continuity in the test event was thus trumped by a more general consideration of temporal synchrony throughout the display.

5.2 *Amodal completion*

Perhaps the central challenge faced by the visual system involves the extraction of a three-dimensional representation from a two-dimensional retina (Marr 1982; Nakayama et al 1995). One necessary step along the path to meeting this challenge involves 'filling in' missing portions of occluded surfaces—a phenomenon known as amodal completion (Kanizsa 1979). The tunnel effect and related demonstrations prove that the visual system is willing to fill in more than just a portion of a static surface, including at times the presence of an entirely occluded object and even an occluded motion trajectory, a phenomenon called amodal integration by Burke and Michotte (Burke 1952; Michotte 1946/1963, 1951/1991). In the same sense that we really perceive an occluded surface, we seem to be able to perceive occluded motion. The current experiments extend our understanding of the kind of information that the visual system fills in amodally. In particular the amodal causal capture phenomenon produces not just the impression of occluded motion, but the impression of an entire sequence of events involving more than one object and with an internal causal structure. This is a rather high-level attribution to make at a location where all the relevant data are not observable directly, and so these results corroborate the growing body of evidence that causality really is an aspect of perception (Leslie 1982). Whenever basic display characteristics imply the presence of causality, we perceive it quickly and irresistibly, even amodally when necessary.

6 Conclusion: Causality in the absence of causality

In his seminal work Michotte argued that the perception of causality possesses the prototypical features of perception: it must be direct and immediate, emerging without influence from language, desires, and expectations, and without prior experience (see Wagemans et al 2006 for a review of Michotte's ideas and influence). Michotte was referring primarily to experience over a person's lifetime, and experimental work has confirmed that very young infants perceive causality according to the same rules as adults (Leslie 1984; Leslie and Keeble 1987; Newman et al 2008). Here we showed that the perception of causality can also emerge without local experience. In several of the demonstrations that we employed, the perception of causality emerged even in instances where no visible causal interaction took place anywhere in the display. Causality was perceived not because a causal launch in one place implies a causal launch in another, but simply because an inferred causal launch in an occluded location afforded the most efficient interpretation of the entire scene. These results imply that causal interpretations are always available to the visual system; they are interpretations that the visual system possesses in advance and applies when deemed necessary, as opposed to interpretations that it constructs from some necessary data. Of course, not everyone agrees with Michotte's view of perception generally (Gibson 1986), and there may well be aspects of perception that are constructed entirely from the ground up, so to speak. But the current results suggest that the perception of causality is an act of perception in exactly the sense that Michotte meant it, the recognition of a categorical type in an impoverished, underdetermined, even amodal stimulus.

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