Research Article

Physically Implied Surfaces

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Abstract
In addition to seeing objects that are directly in view, we also represent objects that are merely implied (e.g., by occlusion, motion, and other cues). What can imply the presence of an object? Here, we explored (in three preregistered experiments; $N = 360$ adults) the role of physical interaction in creating impressions of objects that are not actually present. After seeing an actor collide with an invisible wall or step onto an invisible box, participants gave facilitated responses to actual, visible surfaces that appeared where the implied wall or box had been—a Stroop-like pattern of facilitation and interference that suggested automatic inferences about the relevant implied surfaces. Follow-up experiments ruled out confounding geometric cues and anticipatory responses. We suggest that physical interactions can trigger representations of the participating surfaces such that we automatically infer the presence of objects implied only by their physical consequences.

Our experience of the world goes beyond the light reaching our eyes. For example, an object's perceived color is determined not only by the wavelengths of the light it reflects but also by the inferred conditions of its illumination; an object's perceived size depends not just on its angular extent but also on its apparent distance; and, of course, nearly all visual illusions reflect a discrepancy between retinal stimulation and our subsequent perceptual experience—as when two equal lines appear different in length or a static image appears to move.

However, there may be no better illustration of this principle than when we have impressions of objects that are not even "visible" in the first place, because they cast no light onto our eyes. For example, when an object is partially hidden by an occluding surface, we may infer its continuity behind the surface even though no light from that part of the object reaches us. And in the phenomenon of illusory contours, we experience surfaces that do not exist at all but rather are only implied by other cues, such as coincidental clipping of multiple figures or unified motion against a background (Fig. 1).

Such phenomena are crucial to our experience of a coherent and unified environment. Indeed, object representation is rarely straightforward in the real world, which presents us with a variety of impoverished viewing conditions. Thus, these processes may operate at essentially every moment we see the world and have rightly played a prominent role in theorizing about the nature, function, and development of object processing (e.g., Kellman & Shipley, 1991; Kellman & Spelke, 1983; Nakayama, He, & Shimojo, 1995; Rock & Anson, 1979).

Physically Implied Surfaces?

What kinds of factors can trigger representations of objects that are not there? On one hand, implied objects and the rules governing their creation can be quite rich and sophisticated, incorporating information about perspective, volume, and rigidity (as in, e.g., Fig. 1b; Tse, 1998, 1999; see also Meyer & Dougherty, 1990). On the

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other hand, the kinds of input that are known to give rise to such impressions tend to involve only basic geometric and kinetic factors. For example, coincidental clipping (Fig. 1a) can be characterized in terms of geometric properties, and even known dynamic cues (Fig. 1c) are still explained in terms of straightforward patterns of motion. Could more sophisticated cues play a role?

Here, we explored this possibility by examining the role of physical interactions—bumping, bouncing, colliding, supporting, and other such events—in the representation of objects and surfaces. One clue that events of this sort might play this role comes from a potentially surprising source: stage performers—especially mimes—who can induce vivid impressions of implied objects (such as a wall, rope, or box) simply by seeming to physically interact with them. Even though no light from such objects reaches us (because they do not exist in the first place), a sufficiently convincing physical interaction with an imaginary object—such as appearing to lean on, run into, or climb over a wall—may lead us to infer (and almost "see") that one is there. Such impressions seem to lie somewhere between full-blown visual processing and mere higher-level reasoning—a kind of automatic imagination in which we cannot help but represent the implied participating objects (Nanay, 2010; see also Munton, 2021). Indeed, instances of this phenomenon have been so compelling that they have ignited popular media interest (e.g., the viral "invisible-box challenge"; https://osf.io/w6fty). More generally, attention and cognition are especially tuned to physical interactions in the world. For example, infants are sensitive to causality in displays of collisions (Leslie & Keeble, 1987), and adults readily infer properties of objects involved in physical interactions (Hamrick, Battaglia, Griffiths, & Tenenbaum, 2016; Todd & Warren, 1982; Ullman, Stuhlmüller, Goodman, & Tenenbaum,

Statement of Relevance

How do we know which objects are around us? It might seem as simple as having light from those objects hit our eyes. Yet we also respond to illusory objects that are merely implied such that no light from them reaches us at all. Consider the vivid experiences that mimes induce when they seem to interact with walls, ropes, or boxes. We get a surprisingly clear sense of the size, shape, and location of those objects, even though they do not actually exist. The present work took this experience into the lab by exploring how the mind rapidly and automatically represents the surfaces that people and other objects seem to interact with. How we mentally represent objects in our environment can be driven not only by the objects themselves but also by what happens *to* them.

2018), represent the future states of moving and colliding objects (Gerstenberg, Peterson, Goodman, Lagnado, & Tenenbaum, 2017; see also Guan & Firestone, 2020; Hubbard & Bharucha, 1988; Peng, Ichien, & Lu, 2020), and even form impressions of causal relations mediated by unseen, force-transmitting connecting elements (as in classic "pulling" stimuli; Michotte, 1963; White & Milne, 1997; see also Scholl & Nakayama, 2004).

These observations suggest that objects and surfaces might be inferred from physical interactions themselves in ways that go beyond previously known cues. For example, when an actor appears to lean against an invisible wall, the resulting impression of the wall does not derive from the actor being clipped or occluded (cf. Fig. 1a) or from the motion properties that generate
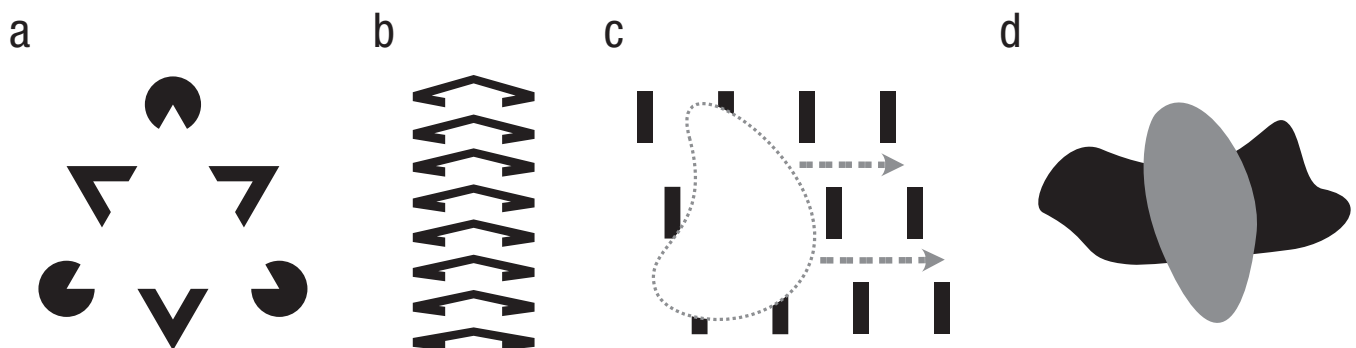
Fig. 1. Illustrations showing how geometric and kinetic cues can give rise to impressions of objects and surfaces that are not actually present. Note the illusory upright triangle in (a) and the illusory tower in (b). In (c), the illusory shape (outlined here by the dashed line) is revealed over time as visible texture elements are accreted and deleted in a dynamic display. Panels (a) through (c) are examples of modal completion, but (d) provides an example of amodal completion, in which the black object appears to be continuous behind the gray occluder. Pictures adapted from (a) Kanizsa (1976); Tse (1998); (c) Palmer, Kellman, and Shipley (2006); and (d) Singh and Fulvio (2007).

other illusory surfaces (e.g., Andersen & Braunstein, 1983; Kellman & Cohen, 1984). Instead, we infer the presence of the wall as an explanation for the otherwise mysterious kinematics of the actor's behavior—as if the mind is asking, "How else could he be leaning like that?" (Rock & Anson, 1979).

The Present Experiments: Invisible Objects Implied by Physical Interaction

Here, we aimed to capture this experience in a laboratory setting. We set aside the question of whether such objects are properly "seen" (see the General Discussion) and instead explored the *automaticity* of such representations—their tendency to arise spontaneously, without instruction, and in ways that interfere with other responses. We showed participants videos of actors colliding with "invisible walls" or stepping onto "invisible boxes" in ways that created vivid impressions of the surfaces they appeared to interact with. After viewing these events, a visible line appeared that either matched or did not match the orientation of the surface implied by the interaction; the participants' task was simply to report the line's orientation, which was completely unpredictable from the preceding event. We reasoned that if the mind automatically infers the surfaces implied by such physical interactions, then responses to visible lines that match (or do not match) these implied surfaces would show a Stroop-like pattern of facilitation of (or interference with) subsequent responses (MacLeod, 1991; Stroop, 1935), even when there is no statistical connection between the events (i.e., even when the nature of the physical interactions are completely task irrelevant; for recent use of such designs in visual cognition studies, see Konkle & Oliva, 2012; Long & Konkle, 2017). Collectively, these experiments explore how physical interactions trigger inferences about the implied participating objects and how those inferences intrude on subsequent responses.

Experiment 1: Running Into an Invisible Wall

Can physical interaction automatically create impressions of invisible surfaces? Experiment 1 tested this possibility using a facilitated reporting paradigm involving videos of a real human actor physically interacting with implied objects.

Method

Participants. A convenience sample of 120 adult participants was recruited from Amazon Mechanical Turk. (For a discussion of this subject pool's reliability, see Crump, McDonnell, & Gureckis, 2013.) This was chosen as a generous sample size in comparison with those of previous visual cognition studies of this sort (typically $N < 40$; e.g., Long & Konkle, 2017; Palmer et al., 2006; White & Milne, 1997). This sample size, as well as all details of the analysis plan and exclusion criteria mentioned below, were preregistered.

Stimuli and procedure. To create the colliding and stepping stimuli, we filmed an actor running into a (real) wall and stepping onto a (real) box. We then digitally removed these objects from the videos to produce the impression that the actor was interacting with an invisible surface. To these modified videos, we added visible candidate "surfaces" whose locations and orientations were either congruent or incongruent with the actor's behavior. In particular, 300 ms after the interaction (i.e., after the actor bounced off the wall or stepped off the box), a black line (6 pixels in thickness) appeared. This line could be either vertical (181 pixels long) or horizontal (96 pixels long) and thus either congruent with the surface implied by the interaction (i.e., a horizontal line after stepping on the box or a vertical line after running into the wall) or incongruent (i.e., a vertical line after stepping on the box or a horizontal line after running into the wall). Because of the nature of online experiments, we cannot specify factors such as the exact size, viewing distance, or brightness of the images as they appeared to participants, because we could not know each participant's particular viewing conditions or display parameters. However, any distortions introduced by a given participant's viewing distance or monitor settings would have been equated across all stimuli and conditions.

Participants' task was simply to report the orientation of the line that appeared, regardless of what interaction came before (Fig. 2a). Note that this design differs from those used in classical biological-motion experiments (e.g., Cutting & Kozlowski, 1977; Kozlowski & Cutting, 1977; Troje & Chang, 2013) in that the focus was on properties of the interacted-with surface rather than on the actor. (For a discussion of biological-motion experiments that do involve manipulated objects, see Experiment 2; Runeson & Frykholm, 1981; Stoffregen & Flynn, 1994.)

Both the original and edited videos are available on this project's OSF page (https://osf.io/sq9td); shorter demos of these displays as they appeared in the experiment can be viewed at https://perceptionresearch.org/mime.

Importantly, the preceding physical events were entirely nonpredictive of the line's orientation: On half of the trials, the line was congruent with the physical interaction, and on half it was incongruent, so the actor's behavior was a completely unreliable cue to the orientation of the line. There were thus four primary trial types, corresponding to the two types of interactions (colliding with a wall or stepping onto a box) and

a

Animation Begins   Interaction   Line Appears
(300 ms After Contact
Is Broken)

b
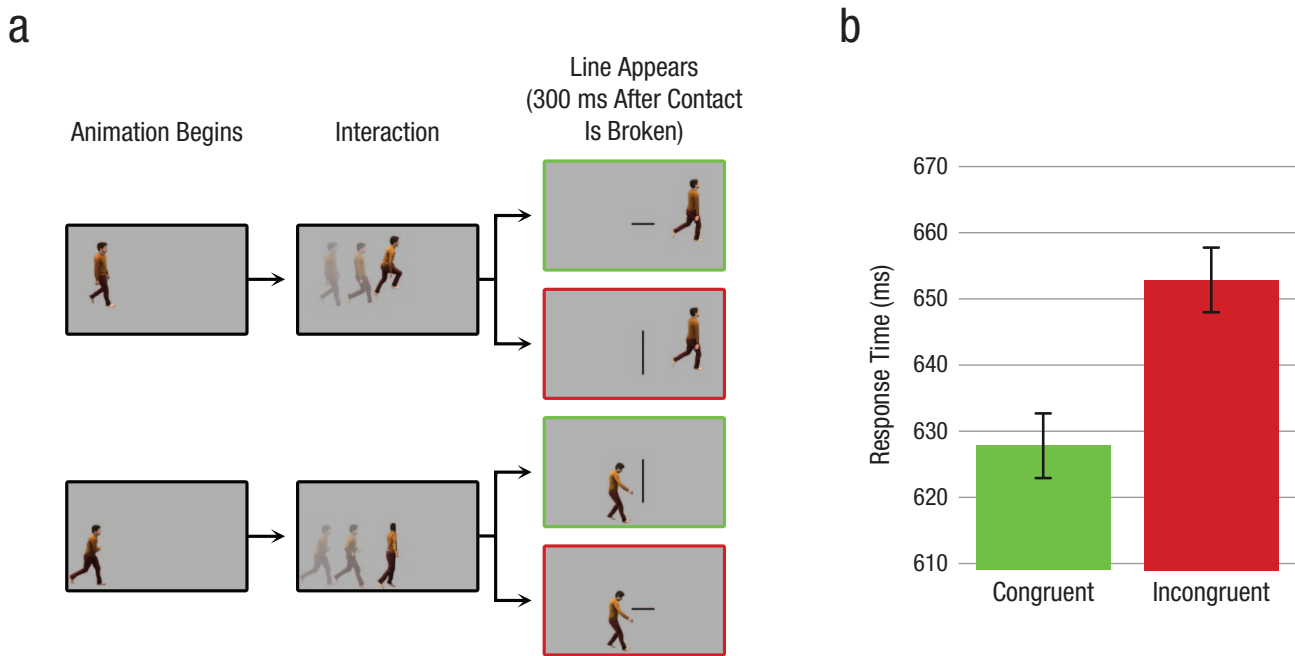
Fig. 2. Design and results of Experiment 1. On each trial (a), participants saw a video in which an actor collided with an invisible wall or stepped onto an invisible box. After the action was performed, a line appeared; participants simply had to report the line's orientation. The graph (b) shows mean response time in the congruent condition (in which the orientation of the line matched the orientation of the surface implied by the actor's motion) and incongruent condition (in which the orientations did not match). Error bars represent ±1 standard error of the mean difference between conditions. Note that the events depicted here are inherently dynamic and cannot be fully captured using static images. Readers who would like to experience the displays as they appeared to participants can do so at https://perceptionresearch.org/mime.

the two line orientations (vertical or horizontal): *wall-vertical* and *box-horizontal* (the congruent trial types), and *wall-horizontal* and *box-vertical* (the incongruent trial types). There were 40 trials total: 10 each of the four trial types. (Half of the trials of each trial type were "mirrored" so that half of the time the actor approached the invisible wall or box from the left of the display and half of the time from the right of the display; however, we collapse over these variants from here onward.) To respond, participants simply pressed the key that was assigned to that orientation (1 or 2, randomly assigned for each participant) and were given 1 s to do so once the line appeared; if they did not respond in this time, a "Too Slow" feedback message was shown, and the trial was not included in the response time analysis.

We reasoned that if the mind automatically infers the invisible surfaces that must be present to explain a physical interaction, then responses to the visible line would be primed or facilitated by first seeing an interaction that implied such a surface—even when such interactions were completely nonpredictive of the visible line's orientation.

Results

In accordance with our preregistered analysis plan, we excluded participants who failed to provide a complete data set or who responded accurately (and within the time limit) on fewer than 80% of trials. Of the 83 participants remaining, accuracy was 91.4%, and mean response time was 640 ms. From these participants, 0.15% of trials were excluded because participants responded too fast (< 200 ms). Thus, the task was fairly easy and straightforward, as expected.

Crucially, participants responded faster when the real, visible line had the same orientation as the invisible surface that had just been implied by the actor's stepping or colliding (Ms = 628 ms vs. 653 ms), $t(82)$ = 5.10, $p < .001$, d = 0.56, 95% confidence interval (CI) for the difference between conditions = [15.28, 34.85] (Fig. 2b). Additionally, they were no less accurate in the congruent condition (M = 92.3%) than the incongruent condition (M = 90.5%). This suggests that the surface implied by the physical interaction was actively represented by the mind such that it could alter later responding. In other words, seeing an actor collide with a vertical wall produced a sufficiently robust impression of a vertical surface that participants were primed to respond to a real vertical surface that subsequently appeared (or, alternately, participants were slower to respond to a surface whose orientation conflicted with the implied interaction, in ways analogous to the phenomenon of Stroop interference, which has recently been applied in visual cognition more generally to

explore similar questions of automaticity; Konkle & Oliva, 2012; Long & Konkle, 2017). We took this result as evidence that physical interactions automatically or spontaneously trigger representations of the surfaces that they seem to imply.

Experiment 2: Idealized Stimuli With "Postdictive" Processing

We are interpreting these facilitated responses as reflecting the physics of the interaction between the actor and the implied surface. However, such physical interaction was perhaps confounded with the shape of the actor's body. For example, in wall trials, the actor necessarily assumed a vertical posture when colliding with the wall; perhaps, then, participants responded more quickly to subsequent vertical lines only because the actor literally appeared more vertical on those trials (in that his body deformed on contact with the vertical wall) rather than because of the implied surface that the actor collided with.

In Experiment 2, we addressed this issue using idealized stimuli that implied surface orientation only "postdictively" (Eagleman & Sejnowski, 2000). Participants saw a rigid disk fall toward—and then bounce off of—an invisible surface. The surface's orientation was implied only by the disk's exit trajectory, which could be either straight up (implying a horizontal surface) or angled (implying an oblique surface). Crucially, the disk contacted the surface only once, and it was its behavior after leaving the surface that retroactively specified the orientation of the surface it must have interacted with. If the same pattern held here as in Experiment 1, this would isolate the present phenomenon to the physics of the interaction per se rather than any confounding geometric cues.

Method

Participants. A sample of 120 adult participants were recruited from Amazon Mechanical Turk. All details of this sample size (as well as the analysis plan and exclusion criteria mentioned below) were preregistered.

Stimuli and procedure. This experiment was identical to Experiment 1 except that the stimuli were now animated displays of a gray disk that dropped down with realistic acceleration under gravity before suddenly bouncing off an invisible surface. On half of the trials, the disk bounced straight back up, implying a horizontal surface; on the other half of trials, the disk bounced off at an angle, implying an oblique surface. Importantly, the disk contacted the implied surface only once and in only a single location (instead of having a spatiotemporally extended interaction). This ensured that the properties of the unseen

surface could be inferred only from the motion of a different object and not on the basis of any visual information from the surface or its boundary. Indeed, this aspect of the design removed a confound that was present not only in our Experiment 1 but perhaps also in previous work exploring representations of objects that are manipulated by biological-motion actors (Runeson & Frykholm, 1981; see also Stoffregen & Flynn, 1994, who cleverly included an object that was not visible at all but that nevertheless still provided multiple samples of its boundary). As in Experiment 1, a visible line (10 pixels in thickness and 250 pixels in length) appeared 300 ms after the bounce. However, here the line was a faint shade of gray only slightly lighter (Hex B5B5B5; half of trials) or darker (Hex ABABAB; half of trials) than the neutral gray background (Hex B0B0B0); the line was either horizontal or rotated 15° clockwise. There were 80 trials total: 20 each of the four trial types, of which half used the lighter gray line and half the darker gray line. Participants' task was simply to report with a key press the orientation of the line that appeared, regardless of what interaction came before, within a time limit of 2 s (Fig. 3a).
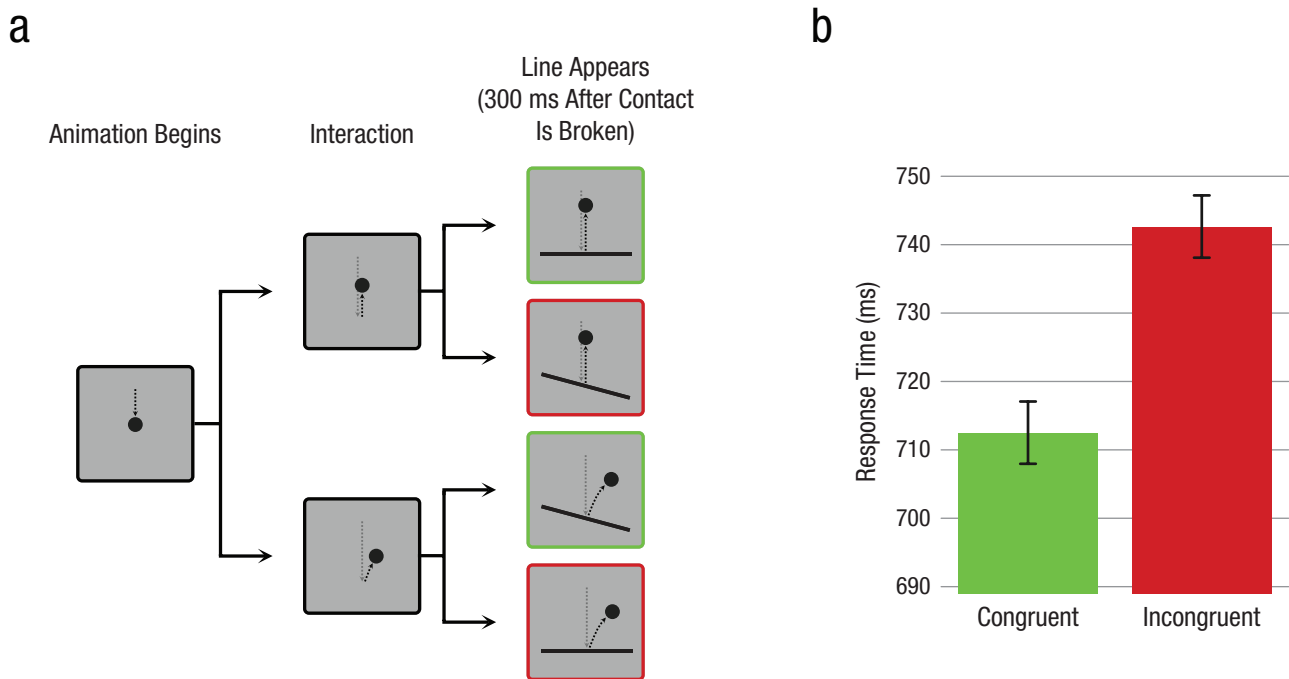
Results

In accordance with our preregistered analysis plan, we excluded participants who failed to provide a complete data set or who responded accurately on fewer than 80% of trials. Of the 106 participants remaining, accuracy was 93.9%, and mean response time was 728 ms. From these participants, 0.35% of trials were excluded because participants responded too fast (< 200 ms).

As in Experiment 1, participants were faster to report the orientation of the line when it had the same orientation as the surface implied by the disk's bounce (Ms = 714 ms vs. 743 ms), $t(105) = 6.41$, $p < .001$, $d = 0.63$, 95% CI for the difference between conditions = [20.32, 38.51]. Unlike in Experiment 1, this pattern can be explained only by the physics of the interaction—in particular, by the exit trajectory of the disk.

Experiment 3: No Delay

The phenomenon we sought to capture would suggest an interaction between the surface representation inferred by participants and their subsequent judgments of the visible surface that then appeared. However, there could be an alternative explanation for the findings of the previous experiments. In particular, it is possible that, on at least some trials, participants prepared a response (on the basis of the preceding physical interaction) during the 300 ms before the visible line even appeared, which could manifest in faster responses for congruent trials in ways that would not require participants to have perceived the visible line at all

Fig. 3. Design and results of Experiment 2. On each trial (a), participants saw a disk bounce off an invisible surface (which it contacted only once) and then exit along a particular trajectory. After this, a line appeared, and participants simply had to report the line's orientation, regardless of the preceding events. Note that in the actual experiment, the lines were a fainter shade of gray than appears here. The graph (b) shows mean response time in the congruent condition (in which the orientation of the line matched the direction of the disk's trajectory after it bounced) and incongruent condition (in which the line orientation and disk trajectory did not match). Error bars represent ±1 standard error of the mean difference between conditions.

(e.g., if they had "made up their minds" before the line was even shown). Though even this interpretation would still suggest a previously unknown influence of physical interactions, we asked in Experiment 3 whether such events could still intrude on judgments of other stimuli even without any delay period in which to prepare a response in advance of the line's appearance.

Method

Participants. A sample of 120 adult participants was recruited from Prolific (Peer, Brandimarte, Samat, & Acquisti, 2017). All details of this sample size (as well as the analysis plan and exclusion criteria mentioned below) were preregistered.

Stimuli and procedure. As in Experiment 2, the stimuli were falling disks that bounced off invisible surfaces—and there were again congruent and incongruent trials (Fig. 4), for a total of 80 trials. However, rather than appearing after a 300-ms delay, the visible line appeared at the very same moment the disk made contact with the implied surface. In the previous experiments including a delay between the interaction with the invisible surface and the appearance of the visible line, participants might have prepared a response (on the basis of that trial's physical interaction) before the line even appeared. But

here, with the line appearing at the moment of contact, that was not possible; instead, participants could not prepare a response until the line actually appeared—which is the central way in which this experiment differed from Experiments 1 and 2.

Even more than in the previous experiments, the disk's exit trajectory here was truly task irrelevant—not only in the weak sense that there was no statistical association between the surface implied by the bouncing behavior and the actual surface that appeared, but also in the stronger sense that the participant could in principle see which visible surface actually appeared before even knowing which surface was implied by the bounces. Thus, this experiment was an especially strong test of the automaticity of implied surfaces from physical interactions: If the bouncing behavior still interfered with participants' responses, this would suggest that they cannot help but compute the orientation of the surface implied by physical interactions and that such inferences directly intrude on judgments about what participants see.

Results

In accordance with our preregistered analysis plan, we excluded any participants who failed to provide a complete data set or who responded accurately on fewer
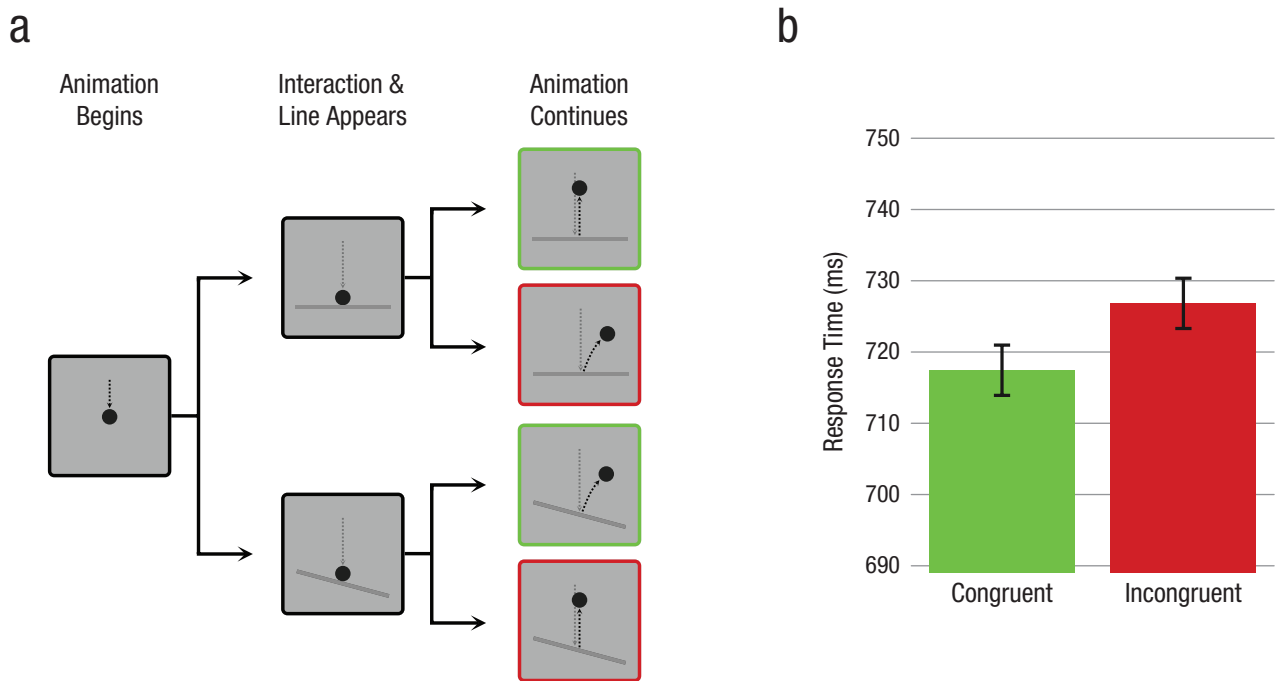
Fig. 4. Design and results of Experiment 3. On each trial (a), participants saw a disk bounce off an invisible surface (which it contacted only once) and then exit along a particular trajectory. At the moment the disk made contact with the invisible surface, a line appeared, and participants simply had to report the line's orientation, regardless of the preceding events. The graph (b) shows mean response time in the congruent condition (in which the orientation of the line matched the direction of the disk's trajectory after it bounced) and incongruent condition (in which the line orientation and disk trajectory did not match). Error bars represent ±1 standard error of the mean difference between conditions.

than 80% of trials. Of the 114 participants remaining, accuracy was 95.4%, and mean response time was 722 ms. From these participants, 0.04% of trials were excluded for being too fast (i.e., responding within 200 ms).

As in the previous experiments, participants reported the orientation of the line more quickly when it had the same orientation as the surface implied by the disk's bounce (Ms = 717 ms vs. 727 ms), $t(113) = 2.66$, $p = .009$; $d = 0.25$; 95% CI for the difference between conditions = [2.40, 16.37]. This suggests that the bouncing behavior influenced participants' responses about which stimuli were shown, even when there was no reason (either in principle or in practice) for it to do so. In other words, whereas Experiments 1 and 2 may have involved prospective anticipation of which surfaces might appear, the present result suggests that physical interactions also influence participants' responses about surfaces *after* they appear.

General Discussion

What can make us represent an object that is not there? Here, we have suggested that physical interaction can automatically trigger inferences about invisible objects or surfaces.[1] When an actor collided with or stepped onto an invisible object, this physical event produced a vivid impression of the implied participating surface, facilitating responses to actual, visible surfaces matching those implied by the actor (Experiment 1). This phenomenon could not be explained by geometric confounds or spatiotemporally extended interactions, and it even occurred postdictively (Experiments 2 and 3); it also generalized between idealized displays and more naturalistic stimuli with real actors. Of course, as in so much visual cognition research, the present task involved only computer displays rather than the real world itself, and these experiments explored only a small region of the possible design space (e.g., in terms of the temporal delay between interaction and line, and the behavioral measures used). Future work could expand on both of these dimensions to further increase the generalizability of these findings or explore lower-level forms of processing (e.g., not only altered responses or judgments but also enhanced contrast sensitivity; Teufel, Dakin, & Fletcher, 2018; though we note that it is controversial whether such methods could apply to the phenomena we explored here; see, e.g., Salvano-Pardieu et al., 2010).

Importantly, these results (involving facilitated or impaired judgments of a visible line) do not establish that perception of the line itself was altered (e.g., that a horizontal line "looks different" or is somehow "harder

to see" when preceded by an actor running into an invisible vertical surface) nor even that the induced surface representation is properly "visual." Instead, our claim is simply that inferences about the surfaces implied by such interactions proceed spontaneously and even automatically, such that they interfere with otherwise straightforward perceptual judgments. In other words, we take our results to show that the mind infers the surfaces implied by physical interactions even without any requirement to do so—and indeed even when doing so actively impairs performance.

The reach of physics

This work adds to a growing literature exploring mental representations of physical events. Whereas classical work on physical reasoning focused on slower and more deliberate judgments about physical systems (e.g., McCloskey, Caramazza, & Green, 1980), more recent work has explored aspects of physical processing that may be faster and more intuitive, including the attentional processes involved in representing the future states of colliding objects (Gerstenberg et al., 2017; see also Chen & Scholl, 2016; Guan & Firestone, 2020; Kominsky et al., 2017), falling towers (Battaglia, Hamrick, & Tenenbaum, 2013; Firestone & Scholl, 2016a), or swinging pendula (Smith, Battaglia, & Vul, 2013; for a review, see Hafri & Firestone, 2021). The present results suggest that such physical representations not only affect judgments of causality, stability, or time (Buehner & Humphreys, 2009) but also trigger representations of objects and surfaces themselves, even when they do not physically exist in the first place. Indeed, this phenomenon highlights an exciting challenge for future computational models of physical intuitions: determining when the behavior of a physical system is sufficiently anomalous that some unseen force or object must be posited to explain it (cf. Carroll & Kemp, 2015).

From the stage to the lab: automaticity and performance

This work also shows how insights from entertainers and stage performers can inform psychological research—an aspiration for many years that is only recently being realized (e.g., Barnhart, Ehlert, Goldinger, & Mackey, 2018; Ekroll, Sayim, & Wagemans, 2017; Yao, Wood, & Simons, 2019). Here, we were inspired by these striking experiences, but we studied them by measuring participants' performance on an indirect task in ways that allowed us to evaluate the automaticity of such processing. Even researchers who previously investigated

impressions of interacted-with objects have typically studied such impressions by asking participants *about* the very experiences under study, but this raises the possibility that such impressions arise only in task-specific ways or even that participants might not have had such impressions if they had not been asked to report them. By contrast, participants' task here—responding to a line—was different from the phenomenon of interest (the surface implied by a physical interaction). Success on this task did not require any attention to the actor's particular behavior or, especially, the disk's exit trajectory; yet such events still influenced performance on the line-identification task, suggesting that participants spontaneously represented such surfaces.

In sum, this work suggests that how we represent objects in our environment—and even whether we represent them at all—can be driven not only by properties of the objects themselves but also by what happens *to* them.

Transparency

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Acknowledgments

Note

1. Note that we do *not* claim to have demonstrated enhanced "perception" of the line that appeared (nor a top-down effect of cognition on perception; Firestone & Scholl, 2016b); all we report is a kind of response interference. Indeed, the two authors of this article disagree about whether the word "visual" even captures the phenomenology of the present demonstrations (e.g., the display in Experiment 1, which also appears at https://perceptionresearch.org/mime). P. C. Little thinks not, because the surface representations evoked by these physical interactions lack seemingly essential properties of visual perception (such as color and spatial extent). C. Firestone agrees that such representations are missing several qualities of full-blown visual experience but nevertheless thinks they have something relevant in common with normal vision. After all, one is not tempted in any way to say that one hears, smells, or tastes the invisible box that the actor steps on—but one is at least somewhat tempted to say that one sees it. However, each author thinks the other makes a good case, and the central question of this article ("Does the mind automatically infer the surfaces implied by physical interactions?") is independent of (a) whether the induced representation is properly visual and, certainly, (b) the nature of any subsequent response interference.

References

Andersen, G. J., & Braunstein, M. L. (1983). Dynamic occlusion in the perception of rotation in depth. *Perception & Psychophysics*, *34*, 356–362.

Barnhart, A. S., Ehlert, M. J., Goldinger, S. D., & Mackey, A. D. (2018). Cross-modal attentional entrainment: Insights from magicians. *Attention, Perception & Psychophysics*, *80*, 1240–1249.

Battaglia, P. W., Hamrick, J. B., & Tenenbaum, J. B. (2013). Simulation as an engine of physical scene understanding. *Proceedings of the National Academy of Sciences, USA*, *110*, 18327–18332.

Buehner, M. J., & Humphreys, G. R. (2009). Causal binding of actions to their effects. *Psychological Science*, *20*, 1221–1228.

Carroll, C. D., & Kemp, C. (2015). Evaluating the inverse reasoning account of object discovery. *Cognition*, *139*, 130–153.

Chen, Y. C., & Scholl, B. J. (2016). The perception of history: Seeing causal history in static shapes induces illusory motion perception. *Psychological Science*, *27*, 923–930.

Crump, M. J. C., McDonnell, J. V., & Gureckis, T. M. (2013). Evaluating Amazon's Mechanical Turk as a tool for experimental behavioral research. *PLOS ONE*, *8*(3), Article e57410. doi:10.1371/journal.pone.0057410

Cutting, J. E., & Kozlowski, L. T. (1977). Recognizing friends by their walk: Gait perception without familiarity cues. *Bulletin of the Psychonomic Society*, *9*, 353–356.

Eagleman, D. M., & Sejnowski, T. J. (2000). Motion integration and postdiction in visual awareness. *Science*, *287*, 2036–2038.

Ekroll, V., Sayim, B., & Wagemans, J. (2017). The other side of magic: The psychology of perceiving hidden things. *Perspectives on Psychological Science*, *12*, 91–106.

Firestone, C., & Scholl, B. (2016a). Seeing stability: Intuitive physics automatically guides selective attention. *Journal of Vision*, *16*(12), Article 689. doi:10.1167/16.12.689

Firestone, C., & Scholl, B. J. (2016b). Cognition does not affect perception: Evaluating the evidence for "top-down" effects. *Behavioral and Brain Sciences*, *39*, Article e229. doi:10.1017/S0140525X15000965

Gerstenberg, T., Peterson, M. F., Goodman, N. D., Lagnado, D. A., & Tenenbaum, J. B. (2017). Eye-tracking causality. *Psychological Science*, *28*, 1731–1744.

Guan, C., & Firestone, C. (2020). Seeing what's possible: Disconnected visual parts are confused for their potential wholes. *Journal of Experimental Psychology: General*, *149*, 590–598.

Hafri, A., & Firestone, C. (2021). The perception of relations. *Trends in Cognitive Sciences*. Advance online publication. https://doi.org/10.1016/j.tics.2021.01.006

Hamrick, J. B., Battaglia, P. W., Griffiths, T. L., & Tenenbaum, J. B. (2016). Inferring mass in complex scenes by mental simulation. *Cognition*, *157*, 61–76.

Hubbard, T. L., & Bharucha, J. J. (1988). Judged displacement in apparent vertical and horizontal motion. *Perception & Psychophysics*, *44*, 211–221.

Kanizsa, G. (1976). Subjective contours. *Scientific American*, *234*, 48–53.

Kellman, P. J., & Cohen, M. H. (1984). Kinetic subjective contours. *Perception & Psychophysics*, *35*, 237–244.

Kellman, P. J., & Shipley, T. F. (1991). A theory of visual interpolation in object perception. *Cognitive Psychology*, *23*, 141–221.

Kellman, P. J., & Spelke, E. S. (1983). Perception of partly occluded objects in infancy. *Cognitive Psychology*, *15*, 483–524.

Kominsky, J. F., Strickland, B., Wertz, A. E., Elsner, C., Wynn, K., & Keil, F. C. (2017). Categories and constraints in causal perception. *Psychological Science*, *28*, 1649–1662.

Konkle, T., & Oliva, A. (2012). A familiar-size Stroop effect: Real-world size is an automatic property of object representation. *Journal of Experimental Psychology: Human Perception and Performance*, *38*, 561–569.

Kozlowski, L. T., & Cutting, J. E. (1977). Recognizing the sex of a walker from a dynamic point-light display. *Perception & Psychophysics*, *21*, 575–580.

Leslie, A. M., & Keeble, S. (1987). Do six-month-old infants perceive causality? *Cognition*, *25*, 265–288.

Long, B., & Konkle, T. (2017). A familiar-size Stroop effect in the absence of basic-level recognition. *Cognition*, *168*, 234–242.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, *109*, 163–203.

McCloskey, M., Caramazza, A., & Green, B. (1980). Curvilinear motion in the absence of external forces: Naive beliefs about the motion of objects. *Science*, *210*, 1139–1141.

Meyer, G. E., & Dougherty, T. J. (1990). Ambiguous fluidity and rigidity and diamonds that *ooze*! *Perception*, *19*, 491–496.

Michotte, A. (1963). *The perception of causality*. New York, NY: Basic Books.

Munton, J. (2021). How to see invisible objects. *Noûs*. Advance online publication. doi:10.1111/nous.12360

Nakayama, K., He, Z. J., & Shimojo, S. (1995). Visual surface representation: A critical link between lower-level and higher-level vision. In S. M. Kosslyn & D. N. Osherson (Eds.), *Visual cognition: An invitation to cognitive science* (pp. 1–70). Cambridge, MA: MIT Press.

Nanay, B. (2010). Perception and imagination: Amodal perception as mental imagery. *Philosophical Studies*, *150*, 239–254.

Palmer, E. M., Kellman, P. J., & Shipley, T. F. (2006). A theory of dynamic occluded and illusory object perception. *Journal of Experimental Psychology: General*, *135*, 513–541.

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

Peng, Y., Ichien, N., & Lu, H. (2020). Causal actions enhance perception of continuous body movements. *Cognition*, *194*, Article 104060. doi:10.1016/j.cognition.2019.104060

Rock, I., & Anson, R. (1979). Illusory contours as the solution to a problem. *Perception*, *8*, 665–681.

Runeson, S., & Frykholm, G. (1981). Visual perception of lifted weight. *Journal of Experimental Psychology: Human Perception and Performance*, *7*, 733–740.

Salvano-Pardieu, V., Wink, B., Taliercio, A., Fontaine, R., Manktelow, K. I., & Ehrenstein, W. H. (2010). Edge-induced illusory contours and visual detection: Subthreshold summation or spatial cueing? *Visual Cognition*, *18*, 591–616.

Scholl, B. J., & Nakayama, K. (2004). Illusory causal crescents: Misperceived spatial relations due to perceived causality. *Perception*, *33*, 455–469.

Singh, M., & Fulvio, J. M. (2007). Bayesian contour extrapolation: Geometric determinants of good continuation. *Vision Research*, *47*, 783–798.

Smith, K. A., Battaglia, P., & Vul, E. (2013). Consistent physics underlying ballistic motion prediction. In *Proceedings of the Annual Meeting of the Cognitive Science Society* (Vol. 35). Retrieved from https://escholarship.org/uc/item/4kr474k3

Stoffregen, T. A., & Flynn, S. B. (1994). Visual perception of support-surface deformability from human body kinematics. *Ecological Psychology*, *6*, 33–64.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643–662.

Teufel, C., Dakin, S. C., & Fletcher, P. C. (2018). Prior object-knowledge sharpens properties of early visual feature-detectors. *Scientific Reports*, *8*, Article 10853. doi:10.1038/s41598-018-28845-5

Todd, J. T., & Warren, W. H., Jr. (1982). Visual perception of relative mass in dynamic events. *Perception*, *11*, 325–335.

Troje, N. F., & Chang, D. H. F. (2013). Shape-independent processes in biological motion perception. In K. L. Johnson & M. Shiffrar (Eds.), *People watching: Social, perceptual, and neurophysiological studies of body perception* (pp. 82–100). New York, NY: Oxford University Press.

Tse, P. U. (1998). Illusory volumes from conformation. *Perception*, *27*, 977–992.

Tse, P. U. (1999). Volume completion. *Cognitive Psychology*, *39*, 37–68.

Ullman, T. D., Stuhlmüller, A., Goodman, N. D., & Tenenbaum, J. B. (2018). Learning physical parameters from dynamic scenes. *Cognitive Psychology*, *104*, 57–82.

White, P. A., & Milne, A. (1997). Phenomenal causality: Impressions of pulling in the visual perception of objects in motion. *The American Journal of Psychology*, *110*, 573–602.

Yao, R., Wood, K., & Simons, D. J. (2019). As if by magic: An abrupt change in motion direction induces change blindness. *Psychological Science*, *30*, 436–443.