Research Report

Psychological Science
2016, Vol. 27(6) 923–930

DOI: 10.1177/0956797616628525
pss.sagepub.com

The Perception of History: Seeing Causal History in Static Shapes Induces Illusory Motion Perception

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Abstract
The perception of shape, it has been argued, also often entails the perception of time. A cookie missing a bite, for example, is seen as a whole cookie that was subsequently bitten. It has never been clear, however, whether such observations truly reflect visual processing. To explore this possibility, we tested whether the perception of history in static shapes could actually induce illusory motion perception. Observers watched a square change to a truncated form, with a "piece" of it missing, and they reported whether this change was sudden or gradual. When the contours of the missing piece suggested a type of historical "intrusion" (as when one pokes a finger into a lump of clay), observers actually saw that intrusion occur: The change appeared to be gradual even when it was actually sudden, in a type of transformational apparent motion. This provides striking phenomenological evidence that vision involves reconstructing causal history from static shapes.

Keywords
shape perception, causality, perceived history

Received 6/30/15; Revision accepted 12/31/15

Causal history leaves visual traces in the present: A dented can, for example, is readily interpreted as an undamaged can that was subsequently dented—and similarly for a bitten cookie or a twisted towel (see Fig. 1). Such observations suggest that even static objects are at root represented in temporal terms, in ways that recapitulate their causal histories. It has been argued that such representations (in which "shape is time") have many theoretical and computational advantages, and that they may serve as a foundation of human cognition (Leyton, 1989, 1992). This notion is also deeply intuitive (e.g., Pinna, 2010), and, indeed, people are readily able to distinguish a shape that has been "bitten" from one that has not, on the basis of various lower-level cues (Spröte & Fleming, 2013).

Perception or Judgment?

It has never been clear, however, whether such observations truly reflect visual processing, or if they are only higher-level cognitive judgments based on visual input. Indeed, perhaps the most trenchant criticism of this proposal has involved the lack of evidence that this sort of interpretation is "automatic, as one might expect from a perceptual system" (Hendrickx & Wagemans, 1999, p. 329), and the observation that, although this idea is "sound enough in mathematical terms, . . . there is little empirical evidence that the nervous system actually parses . . . in this way" (Corballis, 1994, p. 1121).

The Current Study: Motion (in the Present) Inferred From History (in the Past)

The current study explored in an especially direct way whether causal history is extracted as a part of automatic

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Fig. 1. Three examples of inferred causal history in real-world objects. People perceive a bitten cookie as a whole cookie that was subsequently bitten, a dented can as an undamaged can that was subsequently dented, and a twisted towel as a flat towel that was subsequently twisted.

visual processing, by testing whether it can induce the perception of another basic visual property. In particular, we asked whether causal history in visual processing is powerful enough to generate the perception of motion when there is none. In short, we asked: Do people actually perceive history even in static shapes?

Motion is perceived not just as the result of detection, but also as the result of automatic unconscious inferences in visual processing (e.g., Helmholtz, 1910/1925; Rock, 1983). A flash in one location followed by a flash in a different nearby location, for example, is perceived in terms of *apparent motion* of an object between the two locations (for a review, see Dawson, 1991)—and this illusory motion perception also occurs when one shape is replaced with another shape (in what has been called *transformational apparent motion*; Tse, Cavanagh, & Nakayama, 1998). In five experiments, we tested whether inferred causal history can itself give rise to transformational apparent motion.

Experiment 1: Illusory Motion in Static Shapes?

Observers watched a square change to a truncated form, with a "piece" missing, and they reported whether this change was sudden or gradual (Fig. 2a). We asked whether they would mistakenly perceive sudden transformations as being gradual (a type of illusory motion perception in this context) when (and only when) the contours of the missing piece suggested a type of historical "intrusion" (as when one pokes a finger into a lump of clay; see Spröte & Fleming, 2013).

Method

Participants. Six naive observers (with normal or corrected-to-normal visual acuity) from the New Haven, Connecticut, community completed individual 30-min sessions in exchange for a small monetary payment. This sample size was determined via pilot experiments before data collection began.[1]

Apparatus. The experiment was conducted with custom software written in Python with the PsychoPy libraries (Peirce, 2007). The observers sat approximately 60 cm from a 31° × 25° CRT display (without restraint), and all reported sizes were computed on the basis of this distance.

Stimuli and procedure. Each trial began with a 500-ms presentation of a black square (5°) centered on a white background. A truncated square (missing a piece from a randomly chosen side) then replaced it in the same location, as depicted in Figure 2a. We manipulated whether the replacement was sudden or gradual. In *actual-sudden* trials, the truncated square was presented for 500 ms immediately after the whole square. In *actual-gradual* trials, a 17-ms presentation of an intermediate state preceded a 483-ms presentation of the fully truncated square. In both trial types, the truncated square then disappeared, and observers simply pressed keys to indicate whether they saw the change as gradual ("with the missing piece quickly 'growing' into the shape") or as sudden. After a 1-s pause, the next trial began.

Two features of the truncation were manipulated: The *shape* of the missing piece could be any of the four options depicted in Figure 2b (tested simply to generalize the results), and the *contour* could be *imposed* or *intruded*. The critical difference between imposed and intruded contours was that only the latter could have possibly arisen as a result of a historical intrusion event. (The upper left shape in Fig. 2b, for example, could not have arisen through intrusion: If a disc had been "pushed" into the shape, it would have eliminated all of the upper contours in that region, as in the lower left shape in Fig. 2b.)

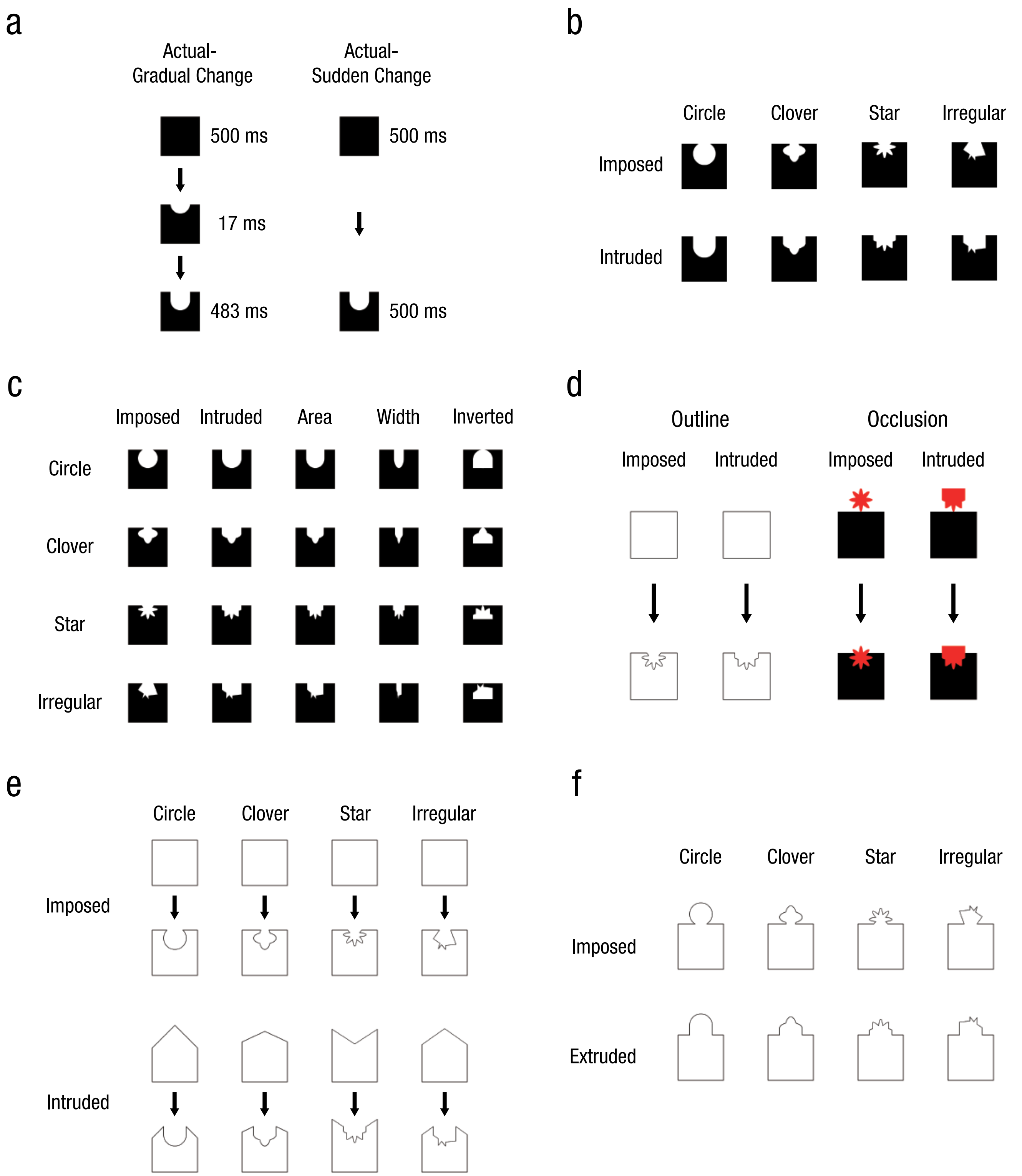

Fig. 2. Depictions of the stimuli used in each experiment: (a) the contrast between actual-gradual and actual-sudden transformations; (b) the contrast between imposed and intruded contours for four different shapes, tested in Experiment 1; (c) the controls for various lower-level geometric properties, tested in Experiment 2 via what we call imposed, intruded, area, width, and inverted contours; (d) the contrast between outline events and occlusion events with imposed and intruded contours, tested in Experiment 3; (e) the contrast between imposed and intruded contours after controlling for turning angles in four different shapes, tested in Experiment 4; and (f) the contrast between imposed and extruded contours for four different shapes, tested in Experiment 5.

Observers completed eight practice trials followed by five 64-trial blocks (2 contour types × 4 shapes × 2 motion types × 4 repetitions, all trials presented in a different random order for each observer), with self-paced rest periods in between consecutive blocks.

Results

The percentages of trials for which observers reported seeing gradual changes are depicted in Figure 3a. Inspection of this figure suggests two primary patterns: (a) Observers had little difficulty distinguishing actual-sudden from actual-gradual transformations (presumably because they looked so categorically different), but (b) observers nevertheless committed false alarms in response to the actual-sudden transformations when they involved intruded contours: They mistakenly perceived these sudden changes as gradual changes more than a quarter of the time. These impressions were verified via the following analyses. A 2 (motion type) × 2 (contour type) × 4 (shape) repeated measures analysis of variance (ANOVA) revealed a main effect of motion type (with actual-gradual motion perceived more often as gradual), $F(1, 5) = 239.43$, $p < .001$, $\eta_p^2 = .980$, and also a main effect of contour type (with intruded contours perceived more often as gradual), $F(1, 5) = 32.14$, $p = .002$, $\eta_p^2 = .865$. Critically, there was also a reliable interaction between these factors, $F(1, 5) = 9.43$, $p = .028$, $\eta_p^2 = .653$, and observers (mistakenly) perceived more gradual motion in actual-sudden trials with intruded contours than in actual-sudden trials with imposed contours (26.9% vs. 7.1%), $t(5) = 4.47$, $p = .007$, $d = 1.82$. In contrast, no such difference occurred with actual-gradual trials (92.3% vs. 89.8%), $t(5) = 1.26$, $p > .250$, $d = 0.51$. These effects generalized to all four of the shapes shown in Figure 2b: Neither the main effect of shape nor any interactions with this factor were reliable (all *p*s > .250).

This effect was also exceptionally reliable nonparametrically, as every single observer perceived more gradual motion in actual-sudden trials with intruded contours than in actual-sudden trials with imposed contours.[2]

Experiment 2: Causal History Versus Lower-Level Geometric Properties

The shapes used in Experiment 1 (Fig. 2b) differed in the causal history they supported, but they also differed in various other lower-level properties that need not correlate with differences in inferred causal history. To ensure that the results reflected only the inferred causal history, we replicated the effect while controlling for the area and opening width of the shapes—and also while testing inverted shapes that eliminate the possibility of intrusion but maintain most other lower-level properties (Fig. 2c).

Method

This experiment was identical to Experiment 1, except as noted here. We tested five different contour types, as illustrated in Figure 2c. The imposed and intruded contours were identical to those used in Experiment 1. In *area* and *width* contours, the intruded contours were horizontally scaled so as to equate area or opening width (respectively) with the corresponding imposed contours. The *inverted* contours were simply inverted versions of the intruded contours. All trials involved actual-sudden changes. Observers completed five 60-trial blocks (5 contour types × 4 shapes × 3 repetitions).

Results

The percentages of trials for which observers reported seeing gradual changes are depicted in Figure 3b. Inspection of this figure suggests a clear pattern: Observers (mistakenly) perceived illusory gradual motion more than twice as often for the three contour types that were consistent with a causal intrusion event (intruded, area, and width contours; $M = 69.0\%$) than for the two contours types that were not (imposed and inverted contours; $M = 32.5\%$). This pattern was readily confirmed with a simple nonparametric binomial sign test, as this pattern held for every single observer ($p = .031$). Moreover, this same pattern was found for every individual shape for every observer—except for a single observer who did not show this pattern with a single shape (circle). Thus, the mistaken perception of gradual motion where there was none in Experiment 1 cannot be explained by appeal to the sorts of lower-level geometric properties that were tested here.

Experiment 3: Outline Versus Occlusion

To further ensure that illusory motion in these experiments was driven by inferred causal history and not by lower-level geometric factors, we tested whether the effect would arise with outlined shapes (in which intruded contours are consistent with causal intrusion events), but not with occluded shapes (in which the very same contours no longer have any inferred causal history; Fig. 2d).

Method

This experiment was identical to Experiment 1, except as noted here. Three factors were manipulated: In addition to testing two types of motion (actual-sudden vs. actual-gradual) and two types of contours (intruded vs. imposed),

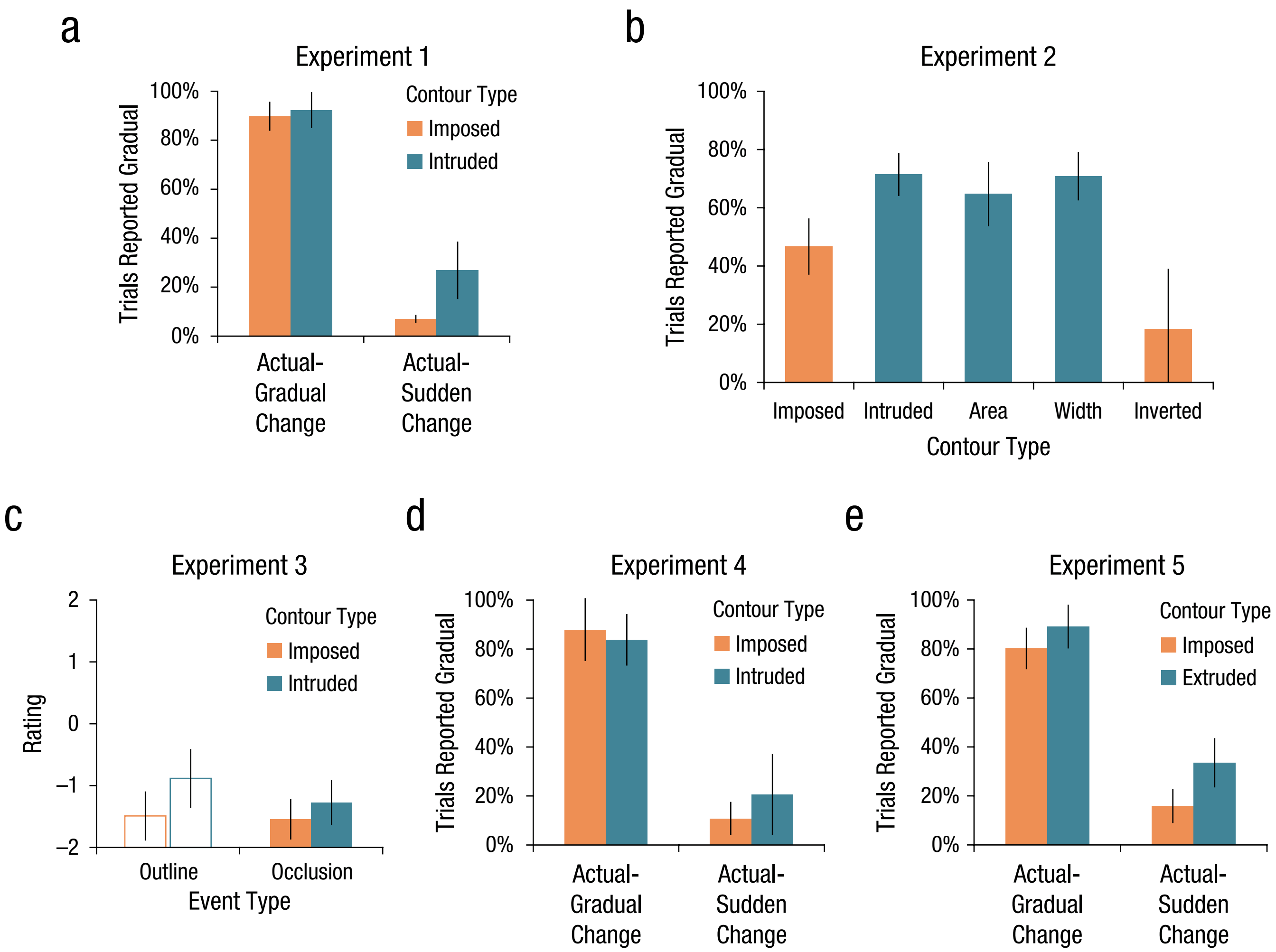

Fig. 3. The primary results from each experiment: (a) the percentage of trials perceived as involving gradual motion in Experiment 1, broken down by contour type and motion type; (b) the percentage of actual-sudden trials mistakenly perceived as involving gradual motion in Experiment 2, broken down by contour type; (c) mean sudden/gradual ratings for actual-sudden trials in Experiment 3, broken down by contour type and event type; (d) the percentage of trials perceived as involving gradual motion in Experiment 4, broken down by contour type and motion type; and (e) the percentage of trials perceived as indicating gradual motion in Experiment 5, broken down by contour type and motion type. Error bars reflect 95% confidence intervals for a within-subjects design.

we tested two event types (each using only the star shape from Fig. 2b): outline versus occlusion (Fig. 2d). In the *outline* condition, each square was drawn only with a black outline (drawn with a stroke of 0.05°), and thus a square with a missing piece unambiguously looked like a truncated square. In the *occlusion* condition, the missing piece was instead a red shape occluding the black square (such that neither shape seemed to be the result of an intrusion event). Observers were asked to rate how gradual they perceived the change on each trial to be, by clicking the computer mouse on a visible 5-point scale (explicitly labeled: *strong gradual*, *weak gradual*, *unsure*, *weak all at once*, *strong all at once*). Observers completed five 80-trial blocks (2 motion types × 1 shape × 2 contour types × 2 event types × 10 repetitions).

Results

Ratings were recoded from −2 to 2, with larger values indicating stronger perceived gradual motion. The ratings for actual-sudden trials are depicted in Figure 3c. Inspection of this figure suggests a clear pattern: The previous causal-history effect for actual-sudden transformations (in which illusory gradual motion was perceived more often for intruded than for imposed contours) was larger for outline trials than for occlusion trials. This impression was verified by the following analyses, which were performed on the recoded data and excluded trials on which observers reported that they were unsure (< 1% of the trials). A 2 (motion type) × 2 (contour type) × 2 (event type) ANOVA revealed a main effect of motion type (with actual-gradual motion perceived more often as gradual), $F(1, 5) = 137.51$,

$p < .001$, $\eta_p^2 = .965$, and a main effect of contour type (with intruded contours perceived more often as gradual), $F(1, 5) = 13.03$, $p = .015$, $\eta_p^2 = .723$, but no main effect of event type, $F(1, 5) = 2.22$, $p = .197$, $\eta_p^2 = .307$. There was also a reliable interaction of these three factors, $F(1, 5) = 23.97$, $p = .004$, $\eta_p^2 = .827$. Most critically, the contrast between intruded and imposed contours for actual-sudden transformations was robust for outline trials, $t(5) = 7.76$, $p = .001$, $d = 3.17$, but not for occlusion trials, $t(5) = 1.97$, $p = .105$, $d = 0.81$, and the Contour Type × Event Type interaction was significant, $F(1, 5) = 12.41$, $p = .017$, $\eta_p^2 = .713$. This causal-history effect was also exceptionally reliable nonparametrically, as every single observer showed a larger difference between intruded and imposed contours for actual-sudden transformations on outline trials compared with occlusion trials.

That the causal-history effect existed only for outline trials (and not for occlusion trials) suggests that the effect may be due to perceived causal history and not to lower-level geometric differences between the shapes themselves, which were equated across these conditions.

Experiment 4: Turning Angles?

To rule out the possibility that the effect is driven by a difference in the turning angles of the contours at the opening of the shape, we tested whether the effect arises when these angles are matched.

Method

This experiment was identical to Experiment 1, except as noted here. All the shapes were drawn only with a black outline (with a stroke of 0.05°). In the intruded condition, a (positive or negative) pentagon instead of a square was used, such that in its truncated form, the two turning angles at the opening of the shape were matched to those in the imposed condition (Fig. 2e). One observer was replaced because of low accuracy in the actual-gradual trials (34.4%).

Results

The percentages of trials for which observers reported seeing gradual changes are depicted in Figure 3d. Inspection of this figure suggests a clear pattern, especially when it is compared with Figure 3a: Just as in Experiment 1, the manipulation of contour type (intruded vs. imposed) had a larger effect on perception of the actual-sudden trials than on perception of the actual-gradual trials. This impression was verified by the following analyses. A 2 (motion type) × 2 (contour type) × 4 (shape) repeated measures ANOVA revealed a main effect of motion type (with actual-gradual motion perceived more often as gradual), $F(1, 5) = 77.75$, $p < .001$, $\eta_p^2 = .940$, and no main effect of contour type, $F(1, 5) = 0.34$, $p > .250$, $\eta_p^2 = .063$, or shape, $F(3, 15) = 2.50$, $p = .100$, $\eta_p^2 = .333$, but a reliable interaction of these three factors, $F(3, 15) = 6.75$, $p = .004$, $\eta_p^2 = .574$. Most critically, there was again an interaction between motion type and contour type, $F(1, 5) = 15.66$, $p = .011$, $\eta_p^2 = .758$.

Given that the simple main effects of contour type in both the actual-sudden and the actual-gradual conditions were not significant, we simply calculated the difference of differences among the four cells in order to interpret the critical interaction. First, for each observer, we subtracted the percentage of trials for which gradual change was reported in the imposed condition from the percentage in which gradual change was reported in the intruded condition, separately for the actual-sudden and the actual-gradual conditions. We then subtracted the difference in the actual-gradual condition from the difference in the actual-sudden condition. A positive difference of differences thus indicated a larger difference in the causal-history effect for actual-sudden transformations compared with actual-gradual transformations. The difference of differences was positive for every single observer.

Experiment 5: A History of Extrusion

In our final experiment, we showed that these results are not specific to shapes involving negative parts (missing pieces), in that they also generalize to inferred causal *extrusion*.

Method

This experiment was identical to Experiment 1, except as noted here. All the shapes were drawn only with a black outline (with a stroke of 0.05°). The final stimulus in each trial was an extended square (i.e., a square with an additional piece added on a randomly chosen side, as depicted in Fig. 2f), instead of a truncated square. The shapes and the contours (now dubbed *imposed* vs. *extruded*) of the additional pieces were the same as those used to form the truncations in Experiment 1.

Results

The percentages of trials for which observers reported seeing gradual changes are depicted in Figure 3e. Inspection of this figure once again suggests clear patterns (which can be summarized by simply noting that this experiment replicated the patterns observed in Experiment 1, depicted in Fig. 3a): (a) Once again, observers had little difficulty distinguishing actual-sudden from actual-gradual transformations, but (b) observers nevertheless committed false alarms in response to the actual-sudden transformations when they involved extruded contours: Observers mistakenly perceived these transformations as gradual changes more than a quarter of the time. These impressions were verified via the following analyses. A 2 (motion type) × 2 (contour type) × 4 (shape) repeated measures ANOVA revealed a main effect of motion type (with actual-gradual motion perceived more often as gradual), $F(1, 5) = 85.44$, $p < .001$, $\eta_p^2 = .945$, and a main effect of contour type, $F(1, 5) = 93.95$, $p < .001$, $\eta_p^2 = .949$, but no main effect of shape, $F(3, 15) = 0.57$, $p > .250$, $\eta_p^2 = .102$. The three-way interaction was not significant, $F(3, 15) = 0.40$, $p > .250$, $\eta_p^2 = .074$. Critically, however, the interaction between motion type and contour type was reliable, $F(1, 5) = 12.05$, $p = .018$, $\eta_p^2 = .707$. Observers (mistakenly) perceived more gradual motion in actual-sudden trials with extruded contours than in those with imposed contours (33.5% vs. 15.8%), $t(5) = 10.12$, $p < .001$, $d = 4.13$, and a weaker (but still significant) effect of contour type occurred with actual-gradual trials (89.2% vs. 80.2%), $t(5) = 4.54$, $p = .006$, $d = 1.85$.

This perception of illusory motion in displays with extruded contours was also exceptionally reliable nonparametrically, as every observer perceived more gradual motion in actual-sudden events with extruded contours than in those with imposed contours for every individual shape—except for a single observer who did not show this pattern with a single shape (irregular).

General Discussion: Seeing History and "Smart Vision"

The key pattern of results from these experiments is simple to summarize: Observers perceived illusory gradual motion when—and only when—the contours were consistent with a causal intrusion (or extrusion) event, and this effect was unlikely to reflect lower-level geometric factors.[3] We note again that this effect was exceptionally robust, occurring for 29 of the 30 observers across all experiments. Readers can experience this effect for themselves online via the dynamic demonstration at http://www.yale.edu/perception/shape-history/.

The effect at the heart of this research is best explained by appeal to inferred causal history. Causal history is intuitively associated far more strongly with higher-level cognition than with perception. The notion that visual processing itself may traffic in such interpretations suggests a way in which vision is richer and "smarter" than it is often given credit for.

In the intrusion condition with actual-sudden transformations, the static contours of the "missing piece" of the square strongly suggested a particular causal history: Just as a bitten cookie looks like a whole cookie that was subsequently bitten, so too these transformations were best interpreted as having resulted from actual intrusion events, wherein one shape was effectively pushed into another shape. Such interpretations have previously been theoretically motivated (Leyton, 1992) and observed for overt judgments (Spröte & Fleming, 2013). But this is the first time, to our knowledge, that such interpretations have been empirically demonstrated to operate in visual processing itself. In our experiments, the intrusion or extrusion interpretation of the events—which effectively imposed a dynamic explanation onto the static shapes—was actually seen to occur. In other words, inferred causal history induced directly perceived motion where there was none. Or, more succinctly, the observers in our experiments actually *saw* the inferred causal history in static shapes unfold.

Action Editor

Alice J. O'Toole served as action editor for this article.

Author Contributions

Y.-C. Chen and B. J. Scholl designed the research and wrote the manuscript. Y.-C. Chen conducted the experiments and analyzed the data with input from B. J. Scholl.

Acknowledgments

For helpful comments, we thank Selena Anjur-Dietrich, Marvin Chun, Chaz Firestone, Frank Keil, Sung-Ho Kim, Stefan Uddenberg, Benjamin van Buren, and Johan Wagemans.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Funding

This project was supported by Office of Naval Research Multidisciplinary University Research Initiative Grant N00014-16-1-2007, awarded to B. J. Scholl.

Notes

1. This sample size was identical for all of the experiments reported here—and as noted later, 29 of the 30 observers across the five experiments showed the same basic effect.
2. Additional surveys (not reported in detail here) confirmed that observers perceive such displays with intruded contours in terms of a single square that is changing its shape because of the intrusion, rather than as a new shape that is occluding part of the square. When asked to simply describe such displays (and how they differ), no observer mentioned a figure-ground contrast, and most descriptions clearly involved a single changing shape. Similarly, when given a forced choice between such options, the majority of observers interpreted all of the events as involving dents occurring in a single shape. See Experiment 3 for a direct contrast between such interpretations.
3. Of course, manipulating perceived causal history requires *some* lower-level visual differences. We ruled out explanations based on area, opening width, turning angle, and all factors

specific to negative parts (as well as factors that were not discussed in the main text, such as maximum width). Nevertheless, intruded shapes still had a greater *ratio* between their opening width and maximum internal width compared with imposed shapes (and mutatis mutandis for extruded shapes). But this difference (a) is a necessary consequence of the manipulation of inferred causal history, (b) is otherwise completely arbitrary and post hoc (although it may relate to part salience), and (c) has never been associated with apparent motion perception. Our results may thus be best explained by appeal to causal history, even though they can always be described in lower-level terms.

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