Visual routines for detecting causal interactions are tuned to motion direction

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Summary

Detecting causal relations structures our perception of events in the world. Here, we determined whether generalized or specialized visual routines underly the perception of causality by assessing the adaptability of specific features in launching events of simple geometric shapes. After prolonged viewing to causal launch events (the adaptor) defined by a particular set of features (i.e., a particular motion direction, motion speed, or feature conjunction), observers were less likely to see causal interactions in subsequent ambiguous test events. We assessed whether this negative aftereffect transfers to test events with a new set of feature values that were not presented during adaptation. Processing in specialized (as opposed to generalized) visual routines predicts that the transfer of adaptation depends on the feature-similarity of the adaptor and the test event. We show that negative aftereffects do not transfer to unadapted launch directions. Crucially, adaptation was contingent on the causal impression in launches as demonstrated by a lack of adaptation in non-causal control events. In contrast, adaptation to launches with a particular motion speed transferred also to a different speed. Moreover, adaptation based on feature conjunctions (color and launch direction) revealed that launch direction trumps the feature identity of the object for causal perception; the adaptation transferred across colors if the test event had the same motion direction as the adaptor. In summary, visual adaptation allowed us to carve out a visual feature space underlying the perception of causality and revealed specialized visual routines that are tuned to a launch's motion direction.

Keywords

Causality; perception; visual cognition; adaptation; direction selectivity

Results

When two objects collide, the objects' future path can be inferred based on physical laws, allowing us, for instance, to purposely change the motion path of an asteroid by steering an uncrewed spacecraft into a collision with the asteroid (see NASA's Double Asteroid Redirection Test; **Figure 1a**). In contrast, how humans detect such causal interactions in their visual environment is less clear. The proposed theories regarding our understanding of causal sensory interactions vary considerably, proposing purely perceptual (Michotte, 1963; Scholl & Tremoulet, 2000), abstract probabilistic (Sanborn et al., 2013), or cognitive mechanisms (Rips, 2011; Weir, 1978; White, 2006). These are neither mutually exclusive nor do they make distinct predictions and they are therefore hard to distinguish (Rips, 2011). Here, we will study the mechanisms underlying the computations of causal interactions by capitalizing on visual adaptation of causality (Kominsky & Scholl, 2020; Rolfs et al., 2013). Adaptation is a powerful behavioral tool for discovering and dissecting a visual mechanism (Kohn, 2007; Webster, 2015) that provides an intriguing testing ground for the perceptual roots of causality. Perceptual accounts of causal understanding posit the existence of visual routines (e.g., cause detectors) located in the visual system, however, their precise nature remain rather hazy. In its purest form such a visual routine could constitute a generalized mechanism that responds to all kinds of causal interactions. Alternatively, there could be many different specialized visual routines for the detection of causality that are tuned to the features of a particular causal interaction (e.g., the direction, kinematics, or object identity; **Figure 1b**; see Rips, 2011 for a discussion). Here, we will use visual adaptation to determine whether the computation of causality occurs in generalized (i.e., feature-invariant) or in specialized (i.e., feature-selective) visual routines. Specifically, we will determine whether or not an adaptor is most effective for test events that match the features of the adaptor.

To this end, we took advantage of the phenomenon that observers perceive causality even in simple kinematic displays—a moving disc that stops next to another disc appears to launch the second disc into motion (i.e., launching effect, **Figure 1c**; Michotte, 1963; see Rips, 2011; Scholl & Tremoulet, 2000; White, 2006, 2017 for reviews). The prolonged viewing of such launching events in an adaptation protocol strongly alters the perception of causality by reducing the proportion of reported launches in subsequent test events (Rolfs et al., 2013). The adaptation of causality is spatially specific to the retinotopic coordinates of the adapting stimulus (Rolfs et al., 2013), suggesting that the detection of causal interactions is implemented locally in visual space. Here, we selected adaptors from a feature space—while keeping their spatial locations constant—and determined whether adaptation transfers to test events with a different set of features in that feature space (**Figure 1b**). If the strength of the adaptation's perceptual consequences depends on the similarity of the adapter and the test event, it would reveal the existence of specialized visual routines for the detection of causal interactions that are tuned to that feature (i.e., there would be multiple visual routines within a feature dimension, each tuned to a different preferred feature value). Alternatively, if we observe adaptation transfer from one feature to another, this will support the notion of a generalized, feature-invariant, visual routine.

In three experiments, we assessed whether adaptation to launches of a particular motion direction, motion speed, or feature identity (i.e., a conjunction of two features) transfers to other values of that feature space or, alternatively, whether the consequences of adaptation are restricted to the feature values of the adaptor. Our results provide compelling evidence for visual routines that are specialized for processing launches of a particular motion direction.

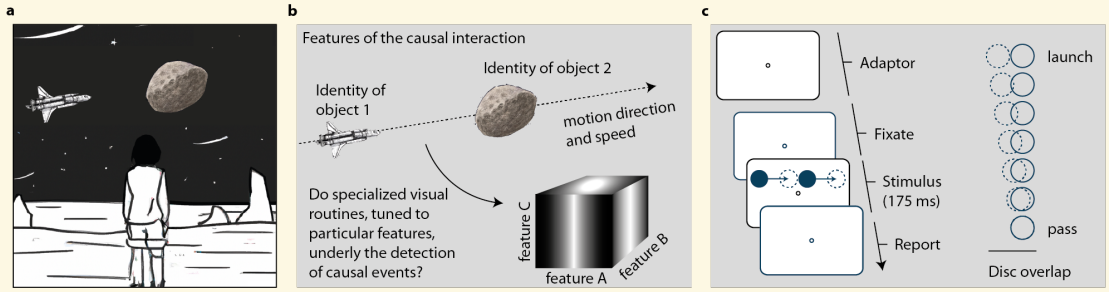

Figure 1. The perception of causality. **a** A person perceiving an upcoming causal interaction between an uncrewed spacecraft and an asteroid. **b** Features of such launching events are the direction and speed of the colliding objects as well as their object identities (i.e., a specific set of features). Assessing the adaptation's transfer between features allows us to determine whether the perception of causality arises in specialized visual routines that are tuned to a particular visual feature. **c** Trial sequence of a test event. A peripheral disc moved towards a stationary disc and stopped with some degree of overlap (ranging from 0–100% overlap in seven equidistant steps) between the two discs. The second disc then immediately started to move in the same direction, with the same speed as the first disc. In adaptation blocks, 320 launches were presented before the first test event of a block, and 16 top-up adaptation events before each subsequent test event.

Adaptation of causality is selective for motion direction.

In **Experiment 1**, we tested whether causality is computed separately within visual routines specialized for different motion directions. To this end, we presented observers with brief test events in one of two possible horizontal directions (from left to right, or right to left) in which a peripheral disc moved swiftly towards a stationary one. The first disc stopped moving as soon as the two discs partially overlapped (the amount of overlap was manipulated in seven steps from zero to full overlap, **Figure 1c**). Simultaneously, the second disc started to move along the same trajectory, and we asked observers to report whether they perceived that the first disc passed the second one (i.e., a pass event; commonly reported at full overlap), or rather launched it into motion (i.e., a launch event; common at zero overlap). We quantified the point of subjective equality (PSE) between perceived launches and passes by modelling psychometric functions for the perception of causality both *before* and *after* adaptation to causal launches (note that we presented the adaptor in a range of ±30° around one of the two possible directions).

This visual adaptation successfully affected the perception of causality in this task. We observed a strong negative aftereffect when test events matched the direction of the launch-adaptor. That is, observers were less likely to report a launch after adapting to launches in the same direction as the test events (**Figure 2a–b**). This observation was corroborated by a two-way (2 event types: launch vs. slip; 2 directions: congruent vs. incongruent) repeated measures analysis of variance (rmANOVA) in which we assessed the magnitude of adaptation by subtracting the PSE before adaptation (PSE_{before} = 0.60, $CI_{95\%}$ = [0.59 0.62]) from the PSEs obtained in each of the four different adaptation conditions (PSE_{cong_launch} = 0.40, $CI_{95\%}$ = [0.36 0.43]; PSE_{incong_launch} = 0.55, $CI_{95\%}$ = [0.54 0.56]; PSE_{cong_slip} = 0.55, $CI_{95\%}$ = [0.54 0.57]; PSE_{incong_slip} = 0.61, $CI_{95\%}$ = [0.59 0.64]). The analysis revealed a significant main effect of event type (F (1, 7) = 62.73, $p < 0.001$; **Figure 2a–b**) demonstrating stronger adaptation for launching than slip events (ΔPSE_{event} = –0.11, $CI_{95\%}$ = [–0.14 –0.08]). Moreover, adaptors in a congruent direction as the test event resulted in stronger adaptation than in incongruent directions (F (1, 7) = 41.62, $p < 0.001$; $\Delta PSE_{direction}$ = –0.11, $CI_{95\%}$ = [–0.15 –0.07]). Critically, we observed a significant interaction (F (1, 7) = 12.23, p = 0.01), revealing that the influence

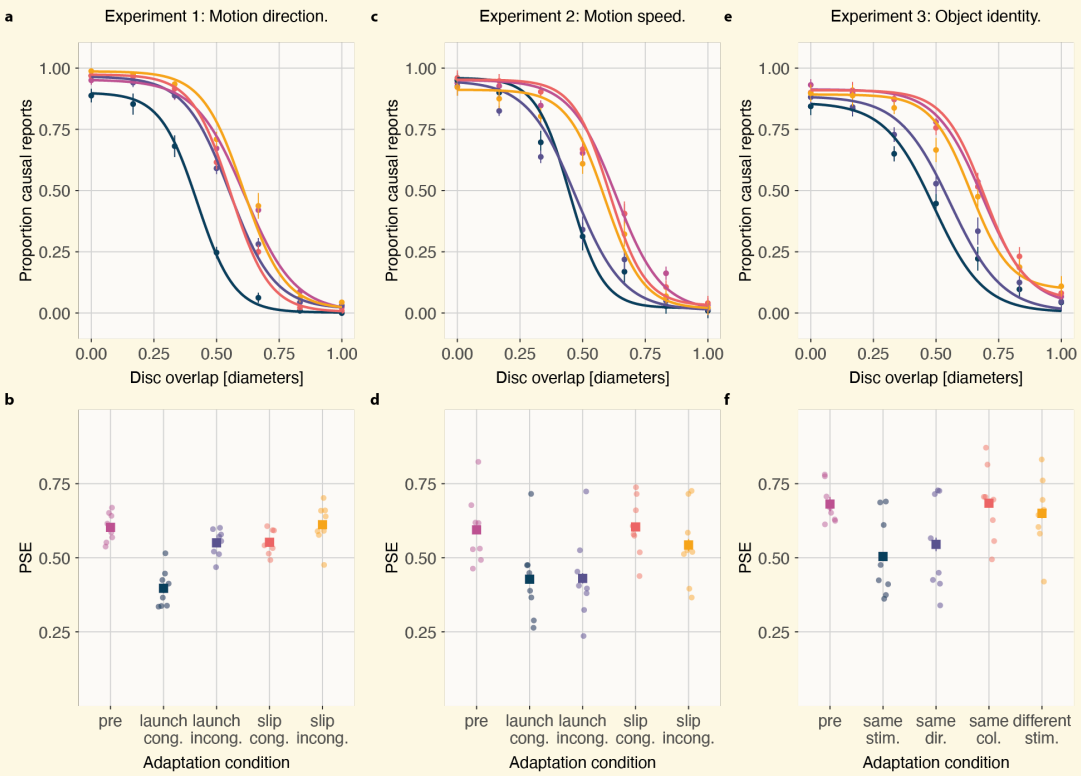

Figure 2. Results of Experiment 1, 2, and 3. **a** Mean proportion of causal reports as a function of disc overlap in Experiment 1. Visualization of psychometric curves is based on the mean parameters averaged across observers before adaptation (pink), and after adaptation with direction-congruent launches (blue), direction-incongruent launches (in purple), direction-congruent slip events (red) and direction-incongruent slip events (in orange). **b** PSEs for each individual observers (circles) and the mean across observers (square). **c** Mean proportion of causal reports as a function of disc overlap in Experiment 2. Visualization of psychometric curves is based on the mean parameters averaged across observers before adaptation (pink), and after adaptation with speed-congruent launches (blue), speed-incongruent launches (in purple), speed-congruent slip events (red) and speed-incongruent slip events (in orange). **d** PSEs for each individual observers (circles) and the mean across observers (square). **e** Mean proportion of causal reports as a function of disc overlap in Experiment 3. Visualization of psychometric curves is based on the mean parameters averaged across observers before adaptation (pink), and after adaptation with adaptors that are identical with the test event (blue), share the same direction but different colors (in purple), same colors but different direction (red) and completely different test events (in orange). **f** PSEs for each individual observers (circles) and the mean across observers (square). All error bars are ± 1 SEM.

of direction-congruency on the magnitude of adaptation was significantly stronger for launches than for slip events (Post-hoc t-test: $t(7) = 3.50$, $p = 0.01$; $\Delta PSE_{eventXdirection} = -0.09$, $CI_{95\%} = [-0.16\ -0.03]$) supporting the hypothesis that specialized visual routines are tuned to the motion direction of launching events.

Adaptation of causality transfers across motion speed.

In **Experiment 2**, we determined whether the perception of causality is also selective for other feature dimensions that are relevant for causal interactions. Causal events in our visual environment encompass interactions of various motion speeds. Here, we examined whether adapting the perception of causality transfers between events that either had different speeds (same as in **Experiment 1** or half that). Both speed-congruent (i.e., test events had the same speed as the adaptor) and speed-incongruent launches (i.e., test events and adaptor differed by a factor of 2) resulted in adaptation, demonstrating a transfer of adaptation across motion speeds (**Figure 2c–d**). As in **Experiment 1**, we corroborated this observation by a two-way rmANOVA in which we assessed differences in the magnitude of adaptation (i.e., the difference in PSEs before and after adaptation; $PSE_{before} = 0.59$, $CI_{95\%} = [0.57\ 0.61]$;

PSE_{cong_launch} = 0.43, $CI_{95\%}$ = [0.40 0.46]; PSE_{incong_launch} = 0.43, $CI_{95\%}$ = [0.39 0.47]; PSE_{cong_slip} = 0.60, $CI_{95\%}$ = [0.57 0.63]; PSE_{incong_slip} = 0.54, $CI_{95\%}$ = [0.50 0.59]) as a function of speed congruency (congruent vs. incongruent speed), event type (launch vs. slip event) and their interaction. The analysis revealed a significant main effect of event type (F (1, 7) = 23.39, p < 0.001; **Figure 2c–d**) demonstrating stronger adaptation for launching than slip events (ΔPSE_{event} = –0.14, $CI_{95\%}$ = [–0.21 –0.07]). Importantly, the magnitude of adaptation was not significantly different for congruent and incongruent speed between adaptor and test event (F (1, 7) = 3.43, p = 0.107; ΔPSE_{speed} = 0.03 $CI_{95\%}$ = [–0.01 0.07]). Moreover, there was no significant interaction between event type and speed (F (1, 7) = 3.48, p = 0.105; $\Delta PSE_{eventXspeed}$ = –0.06, $CI_{95\%}$ = [–0.14 0.02]). These findings demonstrate that the perception of causality is not tuned to motion speed—or, at least, that the tuning is very broad.

Adaptation of causality using feature-conjunctions.

In **Experiment 3**, we determined whether the identities of the two objects involved in the causal interaction can break the observed dominance of the direction-specific computation underlying the perception of causality. For instance, if two visually distinct objects are involved in a causal interaction with one type of object always launching a second, visually distinct object, it is unclear whether the influence of the adaptor is confined to events with the same feature conjunction or, alternatively, whether motion direction is the only relevant feature dimension for determining the presence of causal interactions. To distinguish between these alternatives, the two discs in the presented test events had two different colors (i.e., they were either red or green). Moreover, the adaptor in a session displayed only one particular feature conjunction (e.g., the adaptor in one session was always a red disc on the left launching a green disc on the right into rightward motion; adaptors varied across sessions and each subject saw each combination of feature conjunction across the multiple sessions). In contrast to the adaptor's fixed feature conjunction in a session, both motion direction and color identities in the test events varied randomly from trial to trial. Again, we observed strong adaptation when test events and adaptors were identical. However, when one of the features in the feature conjunction differed, we observed adaptation only for test events in the same direction as the adaptor, irrespective of the object's color. Thus, color does not constitute a critical feature of the visual routine for detecting causal interactions (**Figure 2e–f**). Again, we corroborated this observation by a two-way rmANOVA in which we assessed differences in the magnitude of adaptation (i.e., the difference in PSEs before and after adaptation; PSE_{before} = 0.68, $CI_{95\%}$ = [0.63 0.73]; $PSE_{same_stimulus}$ = 0.50, $CI_{95\%}$ = [0.47 0.53]; $PSE_{same_direction}$ = 0.55, $CI_{95\%}$ = [0.50 0.59]; PSE_{same_color} = 0.68, $CI_{95\%}$ = [0.65 0.72]; $PSE_{different_stimulus}$ = 0.65, $CI_{95\%}$ = [0.61 0.69]) as a function of motion direction (same vs. different), color assignment (same vs. different) and their interaction. The analysis revealed a significant main effect of motion direction (F (1, 7) = 21.07, p = 0.003) demonstrating stronger adaptation for launches in the same as compared to the opposite direction as the adaptor ($\Delta PSE_{direction}$ = –0.14, $CI_{95\%}$ = [–0.22 –0.07]). Adaptation following adaptors with the same color vs. different color assignment were not significantly different (F (1, 7) = 0.071, p = 0.798; ΔPSE_{color} = –0.004, $CI_{95\%}$ = [–0.03 0.03]). However, we observed a marginally significant interaction between color and motion direction (F (1, 7) = 4.59, p = 0.07; $\Delta PSE_{directionXcolor}$ = –0.07, $CI_{95\%}$ = [–0.16 0.01]). Post-hoc paired t-tests showed that color had a marginally significant influence on the magnitude of adapation when adaptor and test events were in same direction (t (7) = 1.97, p = 0.090; $\Delta PSE_{color_samedir}$ = –0.04, $CI_{95\%}$ = [–0.09 0.01]). However, color had no significant influence on

the adaptation of causality when adaptor and test events were in opposite direction (t (7) = 1.97, p = 0.090; $\Delta PSE_{color_opp_dir}$ = 0.03, $CI_{95\%}$ = [–0.02 0.09]).

Discussion

We provide new evidence for the fundamental role of perceptual processes in detecting cause and effect. Using visual adaptation, we revealed that visual routines underly the perception of causality that are specialized for a launch's motion direction but invariant across a broad range of motion speeds. The tuning of causal perception to motion direction reveals a mechanism that is operating locally in feature space and complements previous reports of a spatially specific mechanism residing in retinotopic space (Kominsky & Scholl, 2020; Rolfs et al., 2013).

The observed adaptation is specific to launching events that evoked a phenomenological impression of causality. This implies that adapting simply to the direction of a moving stimulus will only change the input to the visual routine but not the functioning of the routine itself. We controlled for such potential non-causal adapation of low-level featues (e.g., number of stimuli, time of contact, speed, overlap, or simply motion) using carefully designed control events (i.e., slip events) that did not result in comparable aftereffects. Indeed, motion direction constitutes a basic computational unit in vision and can be computed as early as in retinal circuits (e.g., in retinal ganglion cells about 2–3 synapses downstream of photoreceptors in rabbits, Barlow & Hill, 1963). While a retinal origin of launch detection is unlikely, the specialization of visual routines for the perception of causality at the level of individual motion directions raises the possibility that this function is located surprisingly early in the visual system as opposed to a higher-level visual computation. A similar adaptation-based rationale can be applied to study whether different causal interactions can be distinguished from each other by assessing the transfer of adaptation between different causal interactions (Kominsky & Scholl, 2020). While Michotte speculated about three separate causal impressions (i.e., launching, entraining, triggering; see White, 2017 for an extended catalogue of causal interactions) adaptation helped to refine these categories as an adaptation to triggering events transferred to launching events, but adaptation to entraining had no such influence (Kominsky & Scholl, 2020). Thus, adaptation at the category-level of the causal interaction allows to distinguish spezialized detectors for a particual causal interaction. Our findings break down this specialization to a more fundamental level, showing that a specialized visual routine for launching events exists even within separate motion direction channels.

The adaptation transferred across different colors as long as the test events shared the same motion direction as the adaptor. For instance, perceiving a red disc that launched a green disc into motion is also affected by the adaptation of a green disc launching a red disc (i.e., the opposite color assignment) into motion as long as the two events shared the same motion direction. This findings rules out an alternative cognitive mechanism, in which the causing-disc is first identified (e.g., the red disc is identified to launch other discs into motion) and the criterion for detecting a causal interaction would be selectively adjusted only for this particular causing-disc in a top-down manner. Indeed, our results show that the appearance of the objects in the launching event plays only a minor role for adapting the perception of causality (if any), suggesting that the visual system can calibrate the detection of causal interactions independent of the involved object identities.

The existence of specialized visual routines computing causality, however, does not rule out the possibility of a more complex hierarchical architecture that is composed of both specialized and generalized routines. The output of local, specialized detectors within that

architecture could feed into a global, generalized detector. Thus, a weaker response from adapted specialized cause detectors would elicit a weaker response in unadapted global detectors (or super-detectors; Rips, 2011). Indeed, visual adapation to other low-level visual features (e.g., contrast sensitivity) can yield weaker responses during early visual processing which are then passed on to other downstream areas (Kohn, 2007).

Neurophysiological studies support the view of distributed neural processing underlying sensory causal interactions with the visual system playing a major role therein. Imaging studies in particular revealed a network for the perception of causality that is also involved in action observation (Blakemore et al., 2003; Fonlupt, 2003; Fugelsang et al., 2005; Roser et al., 2005). The fact that visual adaptation of causality occurs in a retinotopic reference frame emphazises the role of retinotopically organized areas within that network (e.g., V5 and the superior temporal sulcus). Interestingly, single cell recordings in area F5 of the primate brain even portraited how motor areas are contributing to the perception of causality (Caggiano et al., 2016; Rolfs, 2016), emphasizing the distributed nature of the computations underlying causal interactions, and also stressing that the detection, and the prediction, of causality is essential for processes outside sensory systems (e.g., for understanding other's actions, for navigating, and for avoiding collisions).

Visual adaptation of causality constitutes a powerful tool that allowed us to reveal how specialized visual routines are tuned to the motion direction of a launching event. Visual adaptation in general is thought to be one of the signatures of a perceptual process (Hafri & Firestone, 2021) and therefore is informative for identifiying the visual origin of a mechanism as opposed to, for instance, cognitive accounts (e.g., cognitive schema; see Rips, 2011 for a review). The detection of causal interactions features many hallmarks of perception: An impression of causality emerges fast and automatic for briefly presented stimuli (Michotte, 1963) and causal events reach awareness faster than non causal-events (Moors et al., 2017). The implementation of visual routines for the perception of causality in separate channels of a basic visual feature such as motion direction fortifies the view that our understanding of causal interactions indeed starts as a low-level perceptual routine.

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STAR Methods

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Sven Ohl (sven.ohl@hu-berlin.de).

Materials availability

There are no restrictions for the distribution of materials.

Data and code availability

- The data has been deposited at the Open Science Framework and is publicly available as of the date of publication. [LINK].
- All original code has been deposited at the Open Science Framework and is publicly available as of the date of publication. [LINK].

EXPERIMENTAL MODEL AND SUBJECT DETAILS

In each of the three experiments, we tested eight human observers (Experiment 1: ages 21–32 years; 5 female; 3 male; 8 right-handed; 5 right-eye dominant: Experiment 2: ages 21–30 years; 5 female; 3 male; 7 right-handed; 6 right-eye dominant; Experiment 3: ages 23–30 years; 6 female; 1 non-binary; 7 right-handed; 6 right-eye dominant) in five sessions (1 training session without adaptation, 4 test sessions with adaptation). Based on the data obtained in the session without adaptation (i.e., the first session), we determined whether participants do distinguish between passes and launches in the basic experiment by determining whether the proportion of reported passes increases with increasing disc overlap. We excluded observers that did not distinguish between passes and launches after the first session and replaced them by new observers (resulting in the replacement of one observer in each experiment). Data obtained in the first session (i.e., without adaptation) did not enter the final analyses. In Experiment 1 and 2, we paid observers 8€ per session as compensation for participation and a bonus of 4€ after successful completion of all sessions. In Experiment 3, we paid observers 10€ per session. In all experiments, we obtained observers' written informed consent before the first session. All observers had normal or corrected-to-normal vision and color vision. The study was approved by the ethics committee of the Psychology Department of the Humboldt-Universität zu Berlin and it followed the guidelines of the Declaration of Helsinki (2008).

METHOD DETAILS

Apparatus

Observers sat in a sound-shielded, dimly lit room putting their head on a chin and forehead rest. We controlled for observers' eye position by tracking their dominant eye using an Eyelink 1000 Desktop Mount eye tracker (SR Research, Ottawa, ON, Canada) with a sampling rate of 1000 Hz. We displayed visual stimuli on a video-projection screen (Celexon HomeCinema, Tharston, Norwich, UK) using a PROPixx DLP projector (VPixx Technologies Inc., Saint Bruno, QC, Canada) at a spatial resolution of 1920 x 1080 pixels and a refresh rate of 120 Hz. The screen was mounted on a wall at 180 cm away from the observer. The experiment was running on a DELL Precision T7810 (Debian GNU Linux 8) and implemented in Matlab (Mathworks, Natick, MA, USA) using the Psychophysics toolbox 3 (Brainard, 1997; Kleiner et

al., 2007; Pelli, 1997) for stimulus presentation and the Eyelink toolbox (Cornelissen et al., 2002) for control of the eye tracker. Behavioral responses were collected by pressing one of the two possible keys on a standard keyboard.

General Methods

In our experiments, we asked observers to report whether they perceived a launch or a pass in test events composed of two discs. In the test events, a peripheral disc approached a stationary second disc and stopped at varying disc overlaps across trials (**Figure 1c**). Immediately after that the second disc started moving in the same direction and with the same speed as the first disc. Before the first trial, observers read the instruction for the experiment that was displayed on the screen. As part of the instructions, we presented short demo trials of test events with 0 % overlap that are typically perceived as launches, and test events with full disc overlap, that are typically perceived as a pass. Observers had the opportunity to inspect these two events as often as they wanted. Following the instructions, observers ran a short training session of 14 trials with varying disc overlaps ranging from 0–100 % overlap.

At the beginning of a trial, we asked observers to fixate a gray fixation point (diameter of 1.5 dva) in the center of the screen on a black background and the trial only started after observers successfully fixated the fixation symbol for at least 200 ms. We presented the test events at 3 dva below the fixation symbol. In these test events, the first moving disc (gray; diameter of 1.5 dva) located either left or right from the vertical meridian started moving towards a stationary disc (gray; diameter of 1.5 dva) located 3 dva below the fixation point. The first disc stopped moving at one of seven possible distances away from the stationary disc, resulting in seven different disc overlaps ranging from 0 to 100 %. The entire duration of the test event was 175 ms. At the end of the trial, observers reported whether they perceived a launch or a pass in the test event by pressing either the arrow up key for launches or arrow down key for passes.

The first session served the purpose to determine whether observers perceive launches and passes as a function of disc overlap in our behavioral task. To this end, observers completed 10 blocks with the direction of the test event (2 conditions: left vs right) as well as the amount of disc overlap (7 conditions: ranging from 0–100 % overlap) presented in randomized order in a block. Each combination of these manipulations was repeated two times in a block, resulting in 28 trials in each block and a total of 280 trials in the first session. In sessions 2–5 we presented additional adaptors that varied between the experiments.

Adaptation in Experiment 1

In **Experiment 1**, each observer ran in 15 blocks in each of sessions 2–5. The first 5 blocks in a session were again without adaptation to measure an observer's perception of causality before adaptation. As in the first session, we presented test events in two possible horizontal directions and varied the disc overlap resulting in 28 trials in each block. In blocks 6–15, we presented an adaptor before the first trial of a block. The adaptor was chosen from one of four possible adaptors. In two of the sessions, we used launches in a particular direction as the adaptor (the adaptor's direction was fixed in a session but counterbalanced across sessions). Before the first trial of a block, we presented 320 launching events at the same location as the test events described above. The exact direction of these launching events was randomly chosen from a narrow uniform distribution around the direction on the horizontal meridian (±30 degrees). The long adaptation phase was complemented by a top-up adaptation of 16 launching events in the same direction as the adaptor (again drawn from a narrow uniform

distribution around that main direction) before each trial to maintain an effective adaptation across the entire block. Adaptation to launches from left-to-right and right-to-left were presented in separate and randomly interleaved sessions.

In two additional sessions, we presented slip events as adaptors to control that the adaptation was specific for the impression of causality in the launching events. Slip events are designed to match the launching events in as many physical properties as possible while producing a very different, non-causal phenomenology. In slip events, the first peripheral disc also moves towards a stationary disc. In contrast to launching events, however, the first disc passes the stationary disc and stops only when it is adjacent to the opposite edge of the stationary disc. While slip events do not elicit a causal impression, they have the same number of objects and motion onsets, the same motion direction and speed, as well as the same spatial area of the event as launches. As for the launch-adaptor, we displayed slip adaptors in a narrow uniform range of directions around one of the two possible horizontal directions (from left-to-right or from right-to-left being fixed in a session). This experimental design resulted in four sessions, with separate adaptors that were randomly interleaved across sessions. Overall, each observer ran in a total of 1,680 trials in **Experiment 1**.

Adaptation variations in Experiment 2

In **Experiment 2**, we used a very similar design as in **Experiment 1** with one notable difference. Adaptors and test events varied in motion speed either being the same as in **Experiment 1** or half that speed. Correspondingly, in slow events the test event duration was twice as long (i.e., event duration of 350 ms) as for test events displayed at fast motion speed (i.e., event duration of 175 ms). We presented all test events (and adaptors) always in the same direction (from left to right). Similarly, we also displayed slip events as adaptors in slow and fast motion speeds. Again, in in sessions with adaptation, the first five blocks were without adaptation while blocks 6–15 were with adaptors, each block consisting of 28 trials. Each observer ran in a total of 1,680 trials in **Experiment 2**.

Adaptation variations in Experiment 3

In **Experiment 3**, we determined the transfer of adaptation for feature conjunctions (motion direction x color). The two discs in the test events and during adaptation had different colors (i.e., red and green) and could move in both horizontal directions. In contrast to **Experiment 1 and 2**, slip events were not used as adaptors. This design resulted in four different adaptors that were presented in separate sessions. Again, the first five blocks if a session were without adaptation while blocks 6–15 were with adaptors, each block consisting of 28 trials. Each observer ran in a total of 1,680 trials in **Experiment 3**.

Online control of eye positions

In all experiments, we tracked observers' dominant eye to ensure proper fixation behavior during presentation of the test events and presentation of the adaptors. More specifically, we tracked the dominant eye's current position at sampling rate of 1000 Hz and determined online its distance to the screen center. We aborted a trial, whenever the distance between eye position and screen center exceeded 2 dva. Observers repeated these trials at the end of a block in randomized order. During presentation of the adaptors, we presented a short message (at the fixation point) asking observers to please fixate in the center of the screen once observers gaze exceeded 2 dva away from the screen center.

QUANTIFICATION AND STATISTICAL ANALYSIS

We estimated psychometric functions relating disc overlap to the proportion of reported launches using logistic functions with four parameters for the intercept, slope, as well as upper and lower asymptotes. We fitted these functions separately for each observer and condition and obtained the points of subjective equality (PSE; the amount of overlap between the two discs in the test events that result in the same proportion of reported launches and passes). For inferential statistics, we analyzed PSEs using repeated-measures analyses of variance (rmANOVA). Error bars indicate ±1 within-subject standard error of the mean (SEM; Baguley, 2011; Morey, 2008). A significant interaction in the rmANOVA was complemented by running post-hoc paired t-tests. Please note, one observer in **Experiment 3** showed such a strong negative aftereffect when test event and adaptor were identical, such that the upper asymptote was below a proportion of 0.5 (i.e., the point when launches and passes are equally often reported). Instead of a non-identifiable PSE for that observer in that particular condition, we computed inflection points of the psychometric functions in all conditions for that observer which then entered the statistical analyses.