Voluntary Action Alters the Perception of Visual Illusions

Matti Vuorre and Janet Metcalfe

Columbia University

Corresponding author:

Matti Vuorre

Columbia University

Psychology Dept.

365 Schermerhorn

1190 Amsterdam Avenue

New York, NY, 10027

mv2521@columbia.edu

Abstract

'Intentional binding' refers to the finding that people judge voluntary actions and their effects as having occurred closer together in time than two passively observed events. If this effect reflects subjectively compressed time, then time-dependent visual illusions should be altered by voluntary initiation. To test this hypothesis, we showed participants displays that result in particular motion illusions when presented at short inter-stimulus intervals (ISIs). Experiment 1 used apparent motion, which is perceived only at very short ISIs; Experiments 2 and 2b used the Ternus display, which results in different motion illusions depending on the ISI. In support of the time compression hypothesis, when people voluntarily initiated the displays, they persisted in seeing the motion illusions associated with short ISIs at longer ISIs than during passive viewing. A control experiment indicated that this effect is not due to predictability or increased attention. Voluntary action altered motion illusions, despite their purported cognitive impenetrability.

keywords: time perception; visual perception; agency; volition; action

Introduction

When people judge the timing of their voluntary action and its subsequent effect—say, a button press causing a beep—they retrospectively judge the action and beep as having occurred closer together in time than when they passively observe similar events: Voluntary action seems to compress time. We sought to determine whether this effect (called 'intentional binding'; Haggard, Clark, & Kalogeras, 2002; Moore & Obhi, 2012), occurs because time is perceptually compressed by voluntary actions or whether it only seems so when judged retrospectively.

Although the idea that subjective time can be compressed might seem counterintuitive, people often report the opposite—time slowing (i.e., expanding)—during life-threatening experiences. To investigate whether time really expanded during such events, Stetson, Fiesta and Eagleman (2007) had participants jump off a high tower into a net far below, a manipulation that reliably induced retrospective reports of expanded time. They interposed a visual task during the fall in which digits were presented very quickly—so quickly that under normal conditions the digits fuse and become unreadable. If time had really expanded, participants should have been able to read the digits. However, people's perception of the digits was unchanged. They still fused, indicating that the feeling of expanded time during this frightening experience was retrospective rather than real.

Voluntary actions are thought to compress time, rather than expand it (Haggard et al., 2002). The evidence for time compression, though, is almost exclusively retrospective, and dependent upon reports of when the events occurred—using the Libet clock methodology to elicit retrospective reports of when actions and their effects occurred (Haggard et al., 2002)—or of the time interval between two events (e.g. Engbert, Wohlschläger, Thomas, & Haggard, 2007, who asked participants to verbally estimate the action-effect interval on each trial).

In the only study (Wenke & Haggard, 2009) suggesting that the effect might not be entirely retrospective, participants received two closely spaced successive electric shocks on the finger that moved in the voluntary action condition. Participants needed a longer inter-stimulus interval (ISI) between the shocks to identify them as non-simultaneous following voluntary action. This result was interpreted by the authors as support for the temporal compression hypothesis. But while it is consistent with the temporal compression hypothesis, this result could also have occurred because impaired discrimination occurred for reasons that have nothing to do with time. There may have been sensory overload or numbing of the finger insofar as the shocks were delivered on the same finger that was the source of the action, and which was the locus of the temporal discrimination (e.g. Williams & Chapman, 2002). Although these perceptual effects suggest that time compression might occur as a result of voluntary action, the inference would be more convincing if a phenomenal or perceptual change was manifested in a sensory modality and bodily location that was removed from the action itself.

We conjectured that if time were subjectively compressed by voluntary action, as Wenke and Haggard's (2009) study suggests, then people might perceive time-dependent illusory visual motion differently when they voluntarily initiated the events as compared to when they passively viewed the same events. Specifically, the perceptual time compression hypothesis predicts that people would observe illusions associated with short ISIs at longer objective ISIs following voluntary action, as compared to when they passively viewed the same stimuli.

In Experiment 1, participants observed two successive, spatially offset circles, which, at very short ISIs result in perceived apparent motion (e.g., Kolers & Pomerantz, 1971; Wertheimer, 1912; and see Figure 1A). We varied the ISI over a range in which at the short end people see apparent motion and at the long end they see two separate stationary circles. After each trial, we asked people to indicate whether they observed apparent motion or not. We varied whether they initiated the display with a voluntary button press or watched the display passively. In order to replicate previous findings of intentional binding using time estimation reports, in a separate task, using the same stimuli, participants retrospectively estimated the ISI. If the effect of voluntary action was subjective time compression then both the retrospective reports and the illusory perceptual motion effects, just outlined, would be in evidence: voluntary action would result in perceived apparent motion at longer ISIs, and in, overall, longer estimates of the ISIs than would passive viewing. If intentional binding were only retrospective, however, then there should be no difference in the perceptual reports of illusory motion, but there should still be a difference in participants' retrospective reports of time as a function of whether they initiated the movement or not.

Experiment 2 used the Ternus illusion in which two horizontally aligned circles are presented, such that the rightmost circle is shown mid-screen (Ternus, 1926). After an ISI, the two circles are shown such that the left circle is mid-screen, and the rightmost circle is offset to the right (Figure 1B). With sufficiently short ISIs, observers perceive the leftmost circle leapfrogging over the center circle to land on its other side (‘element motion’). At longer ISIs the two circles appear to move in tandem (‘group motion’). We varied both the ISI and whether the participants voluntarily initiated the display or just passively watched, and asked whether they observed element or group motion. To ensure the reliability of our findings, we conducted a direct replication of Experiment 2 (Experiment 2b).

Experiment 1

Method

Participants. Twenty-four Columbia University undergraduates participated for course credit. We aimed for a similar sample size as reported in previous studies (Engbert et al., 2007: *n* = 18; Wenke & Haggard, 2009: *n* = 19). One participant quit the study before the interval estimation task, otherwise all participants completed both tasks, and always completed the apparent motion task first. We chose this order to ensure that participants would not carry perceptual learning or response biases from the interval estimation task to the apparent motion task, which was the main target of inference in the current study.

The experiment was approved by the Columbia University Internal Review Board, and was carried out in accordance with the Psychonomic Society ethical guidelines and with the Declaration of Helsinki.

Apparent Motion Task. The design was a 2 (Action Condition: voluntary action, no action) by 8 (inter-stimulus interval (ISI): 33, 50, 83, 100, 133, 150, 200, 300 milliseconds) within-participants factorial. The primary dependent measure—judgment of apparent motion—was a binary (yes or no) response. Action Condition was manipulated between 4 counterbalanced blocks of 80 trials each. ISI was randomized between trials, resulting in 20 trials of each ISI-Action Condition pair, and a total of 320 trials per participant.

Participants completed the experiment individually on an Apple iMac computer, running at a 60 hz refresh rate, in a dark testing room. They were seated approximately 60cm from the monitor, and wore headphones throughout the study. At the beginning of the study, the participants read through the experiment instructions, and were instructed that the experiment was about motion perception. Before each block, on-screen instructions indicated which action condition the next block would represent. For voluntary action blocks, the instructions read: “In the next trials, press the mouse button to initiate the display. Press the mouse button whenever you wish to do so.” For no action blocks, they read: “For the next trials, please remove your hand from the mouse. The display will initiate automatically.”

At the beginning of each trial, participants observed a black fixation cross within a small rectangle located in the center of the screen. In the voluntary action condition, they fixated on the cross until they pressed the mouse button. Immediately, a black circle (diameter = 5mm [~ .4°], duration = 83 ms) flashed in the lower left of the rectangle, followed, after the designated ISI, by an identical circle 15mm to the right from the first circle. The midpoint of the apparent motion path was 10mm below the fixation point. 600 ms after the second circle disappeared, the fixation cross disappeared and two lines of text appeared below the rectangle, reminding the subject to press ‘1’ if they saw motion, or ‘2’ if they did not. The chosen response was highlighted for 500ms, and another trial began after a 500ms inter-trial interval. The experiment was programmed with the OpenSesame software package (Mathôt, Schreij, & Theeuwes, 2012). A schematic of the apparent motion stimuli is shown in Figure 1A.

The no action condition was the same as the voluntary action condition except that instead of pressing the mouse button, participants fixated on the cross until the first circle automatically appeared after a random delay (from a uniform distribution of 500 - 3500ms). The onset of the first circle was paired with a recorded mouse click sound to equate the auditory stimulation across conditions (see Humphreys & Buehner, 2010; Kawabe, Roseboom, & Nishida, 2013). We did not include a 'passive' movement condition in which the finger is moved by something other than the participant, because we were interested in comparing the effects of voluntary actions to passive viewing. We were concerned that having one’s finger moved by a machine—as is usual when this condition is included—might startle, surprise, or lead to reorienting attention away from the main task, which might interfere with perception. Each participant completed the task in approximately 30 minutes.

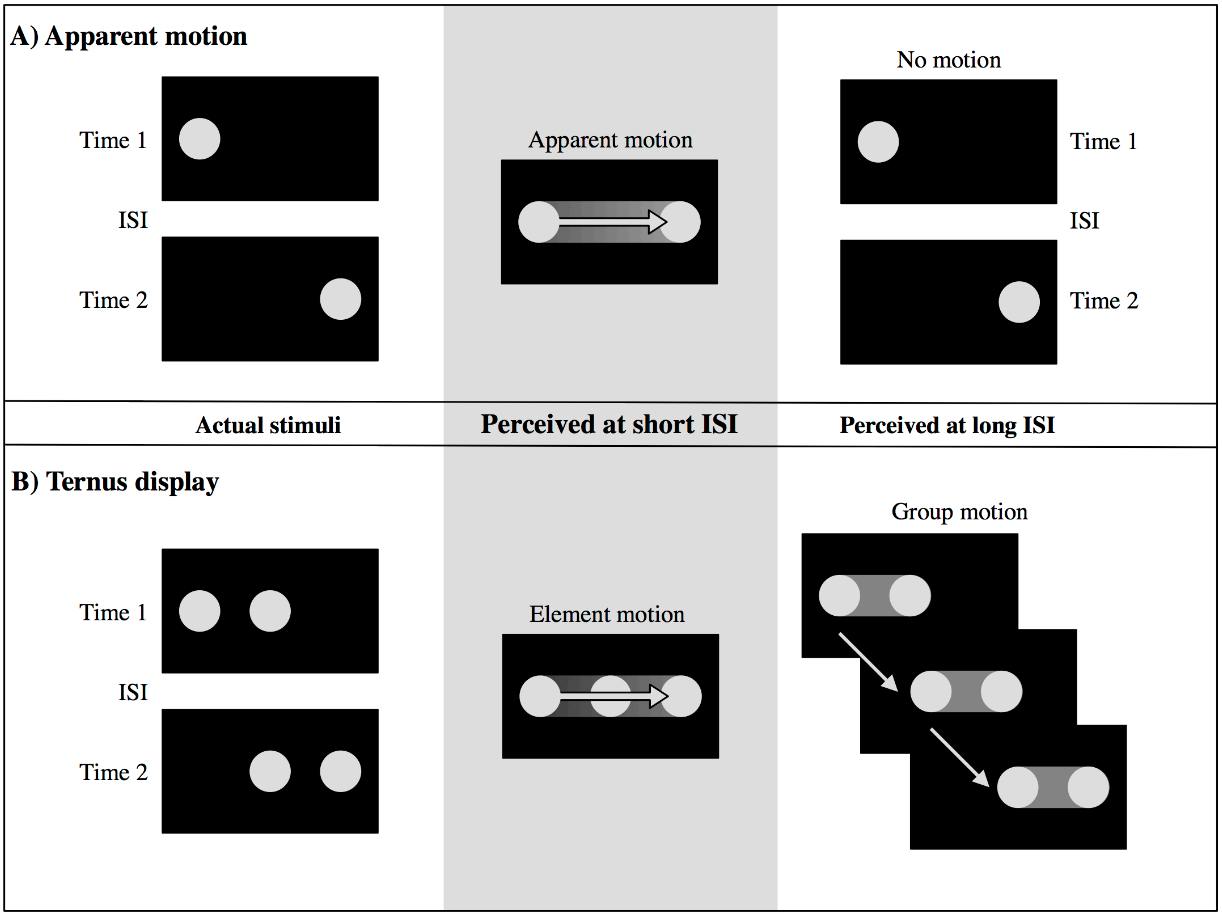

Figure 1. The two visual illusions used in the study. **A)** Experiment 1: Apparent motion. When two spatially separated successive visual stimuli are presented with a short enough inter-stimulus interval (ISI), people observe apparent motion, whereby the first stimulus appears to move to the location of the second stimulus. When the ISI is too long, people see two separate and successive stimuli. **B)** Experiment 2: Ternus display. Two successive, horizontally displaced, pairs of visual stimuli are presented such that the rightmost stimulus in the first pair is located where the leftmost stimulus is located in the second pair. With short enough ISI, people see element

motion, whereby the outermost stimulus leapfrogs over the middle stimulus, which remains stationary. If the ISI is too long, people see group motion, whereby the pair moves in tandem.

Interval Estimation Task. The interval estimation task was conducted after participants had completed the apparent motion task. It consisted of a 2 (Action Condition: voluntary action, no action) by 4 (ISI: 50, 150, 250, 350 ms) within-participants design. Action Condition was manipulated within 4 counterbalanced blocks of 40 trials each, and ISI was randomized between trials in each block, resulting in 20 trials of each ISI-Action Condition pair and a total of 160 trials per participant. After each display, participants responded to the question “How long was the interval between the two circles, in milliseconds?” by typing a number with the computer keyboard. This procedure follows that of Engbert et al. (2007). Participants were informed at the beginning of the task that the interval would always be between 1 and 500 ms. The task took approximately 30 minutes.

Results

Apparent motion. While we chose the range of ISIs to capture the ISIs over which most participants see apparent motion as sharply declining function of ISI (Kolers & Pomerantz, 1971) there is variability in this percept (Ekroll, Faul, & Golz, 2008). For our purposes, there would be no possibility of measuring a difference between conditions if a participant failed to show any sensitivity to ISI in the range of ISIs investigated. We therefore rejected participants who did not show at least a 10% decline in apparent motion responses from the shortest ISI to the longest, averaged over both conditions. This rule excluded four participants and left a final sample size of 20 participants. Additionally, one participant quit the study before the second voluntary action block. Otherwise no trials were excluded.

Voluntary actions increased apparent motion perception, as shown in Figure 2. A Bayesian multilevel logistic regression[1] model showed that voluntary actions increased apparent motion perception ($\hat{\beta}$ action = 0.51, 95% CI [0.07, 0.99], posterior probability = 98.8%, z[2] = 2.50, p = 0.01). We estimated the magnitude of the perceptual shift by comparing the average 50% motion perception thresholds (point of subjective equality, PSE) between conditions. The PSE was 19 ms higher in the voluntary action condition, indicating that people perceived apparent motion with longer ISI in the voluntary action condition ($\text{PSE}_{\text{voluntary}}$ = 113 ms, 95% CI [84, 142]; $\text{PSE}_{\text{no action}}$ = 95 ms, 95% CI [60, 126]; difference in PSE (voluntary action – no action) = 19 ms, 95% CI [2, 38]). The posterior probability for a positive shift in PSE was 98.3%.

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[1] We used minimally informative priors to constrain the parameter estimates on the log-odds scale. We used Normal(0, 100) distributions as priors for the population-level (fixed) regression coefficients, $\text{Cauchy}^{+}(0, 4)$ priors for the participant-level (random) coefficient SDs. We also estimated the model using standard maximum likelihood methods (Bates, Mächler, Bolker, & Walker, 2015), which led to identical conclusions. For parameters estimated with the Bayesian model, we report posterior means ($\hat{\beta}$) and their associated 95% Credible Intervals (CI; the central 95% of values in the respective marginal posterior distribution.) All Bayesian inference was done via Hamiltonian Monte Carlo sampling as implemented in the Stan programming language, and the posterior samples were analyzed using R (Buerkner, 2016; R Core Team, 2016; Stan Development Team, 2016).

[2] p, t, and z-values are from models estimated with classical maximum likelihood methods.

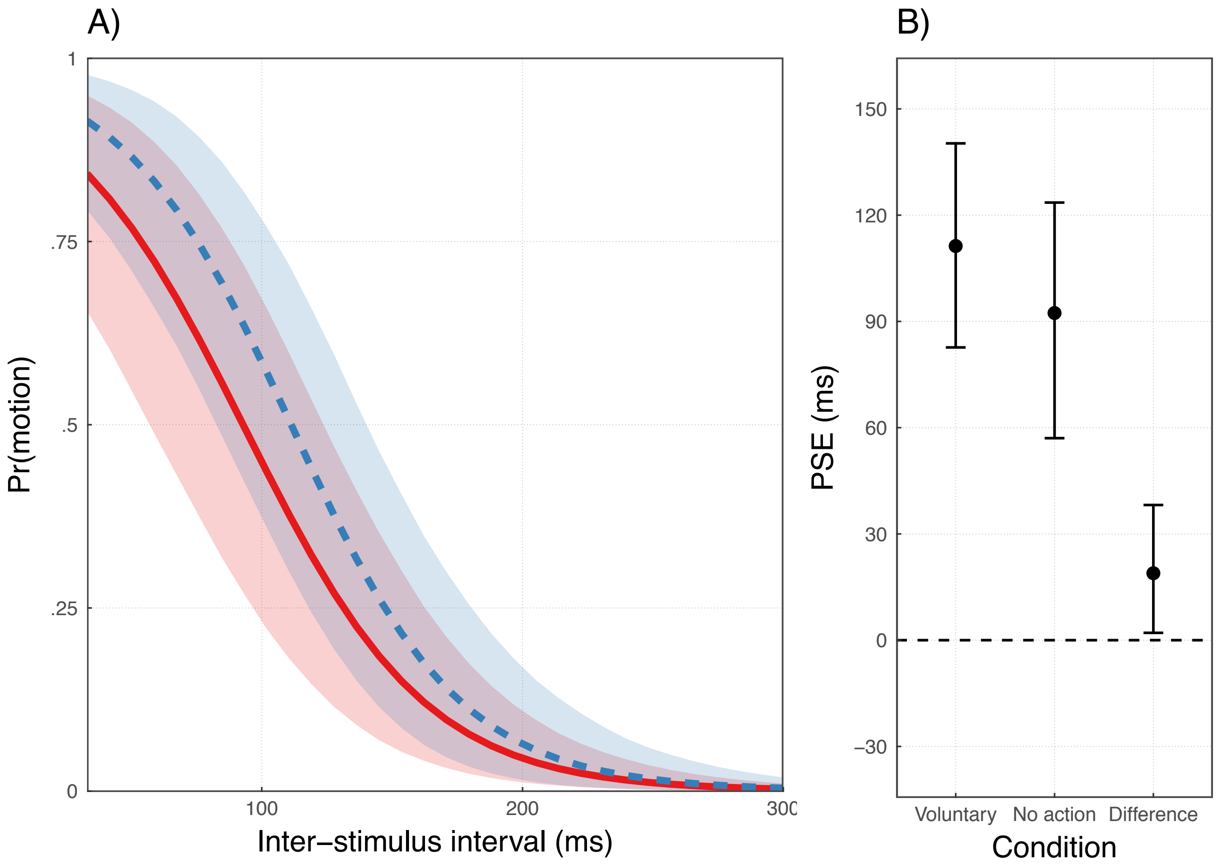

Figure 2. Multilevel logistic regression model of the apparent motion task, Experiment 1. A) Average model-predicted probabilities of apparent motion for the no action (red) and voluntary action (blue, dashed) conditions, with 95% CIs as light shades. B) Points of subjective equality in both experimental conditions, and their difference (voluntary action – no action). Error bars are 95% CIs.

Interval Estimation. Before analyzing the interval estimation data, we removed 29 trials—out of a total of 3040—because they had responses outside the accepted range (1 – 500ms). One participant quit the study before the interval estimation task, resulting in 19 participants' data included in the analysis.

We analyzed the interval estimation data using a Bayesian multilevel linear regression model. As expected from previous literature on intentional binding (Engbert et al., 2007), interval estimates were shorter in the voluntary action condition (Figure 3). On average, participants gave 25 ms shorter estimates in the voluntary action condition (95% CI [-41, -9.4], $t_{(18)} = -3.47$, $p = 0.003$). ISI and action condition did not interact.

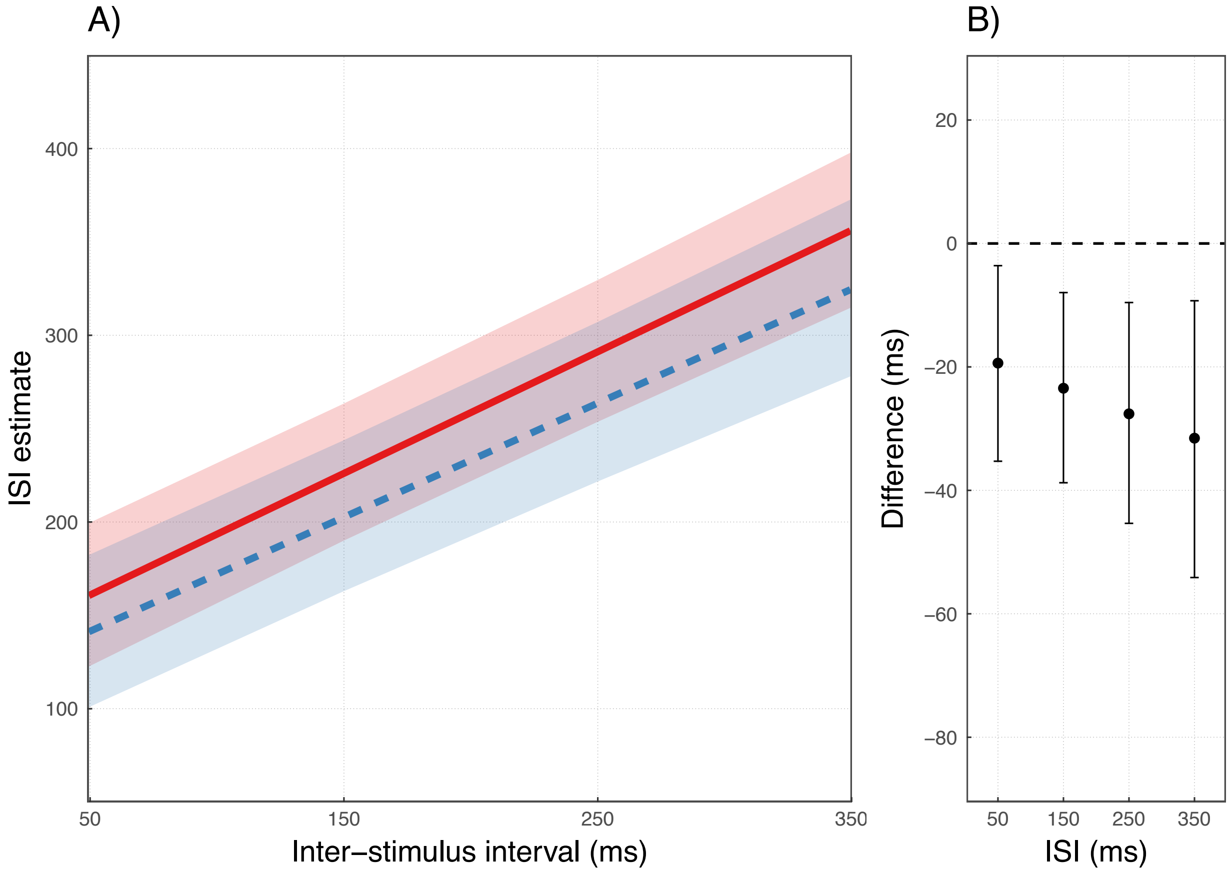

Figure 3. Multilevel regression model of the interval estimation task, Experiment 1. A) Average model-predicted interval estimates for the no action (red) and voluntary action (blue, dashed)

conditions, with 95% CIs as light shades. B) Difference in interval estimates (voluntary action – no action) for each ISI, error bars are 95% CIs.

Discussion

Experiment 1 showed that people saw the illusion of apparent motion at longer ISIs when they voluntarily initiated the display as compared to when they viewed it passively. This differential perception of the visual illusion of motion appears to reflect voluntary-action-induced compression of subjective time.

A possible concern, though, is that voluntary actions might somehow bias or prime participants to report motion. The fact that the finger moved might have triggered the idea of movement that was then reported as more apparent movement in that condition. In contrast to this concern, the perception of apparent motion is usually thought to be cognitively impenetrable (Dawson, 1991), making it unlikely that there was some selective priming of 'motion' in the voluntary action condition. Nevertheless, to address the possible issue of priming or biasing, in Experiment 2, we used the Ternus display in which motion, but *different types* of motion, is perceived at short and long ISIs. Using another illusion also allowed us to conceptually replicate our findings from Experiment 1.

Experiment 2

Method

Experiment 2a was similar to Experiment 1, except that the Ternus display was used (please see Figure 1B.) The Ternus display consists of two horizontally aligned pairs of visual stimuli. The first pair is shown such that the rightmost object is at the center of the display, then, after a brief ISI, another pair of stimuli is presented such that the leftmost object is at the center of the display. If the ISI is short, people see element motion, whereby the outermost object jumps across the display and the central object seems stationary. With long ISIs, people see group motion, whereby the pair of objects seems to move together.

Participants. Thirty-six Columbia University undergraduate students participated in the experiment in exchange for course credit. The increase in sample size allowed us to repeat each counterbalance condition six times instead of four times over all participants. The experiment was approved by the Columbia University Internal Review Board, and was carried out in accordance with the Psychonomic Society ethical guidelines and with the Declaration of Helsinki.

Ternus display task. We used a 2 (Action Condition: voluntary action, no action) by 10 (inter-stimulus interval (ISI): 0, 13, 27, 40, 53, 67, 80, 93, 107, 120 milliseconds) within-participants design. The dependent measure—type of motion perceived—was measured as a binary (element or group motion) response. Action Condition was manipulated within 4 counterbalanced blocks of 120 trials each, and ISI was randomized between trials, resulting in 24 trials of each ISI-Action Condition pair, for a total of 480 trials per participant.

Participants completed the experiment individually on a Dell desktop computer, running at a 75hz refresh rate, in a dark testing room. They were seated approximately 60cm from the monitor, and wore headphones throughout the study. At the beginning of the study, the participants were instructed that the experiment was about different types of motion percepts. Before the experiment, they read the following instructions: “In this task, we ask you to observe brief visual stimuli on the screen, and report what you see. Specifically, we will show you a display called the Ternus display. In the Ternus display, you will see two circles flash on the screen, then another two circles flash slightly to the right of the first two circles. This can lead to two different types of motion perception. The first, called element motion, looks as if only the outermost circle moved from the left-most position to the right-most position, while the middle circle remained stationary. The second type of motion perception is called group motion, and looks as if both circles moved right." They also saw an image similar to Figure 1B. They then passively observed 34 demonstration trials of the Ternus display; 12 trials with short intervals (0 and 13ms ISI), 12 trials with long intervals (120 and 133ms ISI), and 10 trials with the intervals used in the actual experiment. Participants did not provide responses during the demonstration trials.

The experiment was identical to Experiment 1 apart from the following changes to the visual stimuli. After the fixation cross disappeared, two dark gray Gaussian circles (diameter = 8mm [~ .7°], frequency = 0.001, SD = 6, duration = 67ms) flashed under the fixation cross, one directly under it, and the other one displaced 16mm to the left, followed ISI later by two identical circles, one again in the middle, and the other one displaced 16mm to the right. The middle circle was placed 8mm below the fixation point. 600ms after the second pair of circles disappeared, the fixation cross disappeared and two lines of text ('Element motion'; 'Group motion') appeared below the rectangle. Participants provided unspeeded responses, and pressed 'E' for element motion, and 'G' for group motion. The chosen response was highlighted for 500ms, and another trial began after a 500ms inter-trial interval. Each participant completed the task in approximately 30 minutes.

Results

We used the same exclusion criteria as in Experiment 1: 3 participants were rejected because their element motion responses were not sensitive to changes in the ISI. Additionally, two participants reversed their response buttons; their data was included after reversing their responses.

People persisted at seeing the illusory percept associated with shorter ISIs (element motion) at longer ISIs when they initiated the display with voluntary action (Figure 4). A Bayesian multilevel logistic regression model[1] showed that voluntary actions increased element motion perception ($\hat{\beta}$ action = 0.38, 95% CI [0.17, 0.60], posterior probability = 99.9%, $z = 3.81$, $p = 0.0001$). We quantified the perceptual shift using the 50% element motion thresholds (point of subjective equality, PSE). The PSE was 7.7 ms higher in the voluntary action condition than in the passive condition ($\text{PSE}_{\text{voluntary}}$ = 49 ms, 95% CI [43, 56]; $\text{PSE}_{\text{no action}}$ = 41 ms, 95% CI [35, 48]; difference between PSE (voluntary – no action) = 7.7 ms, 95% CI [3.6, 11]). The posterior probability for a positive difference in PSE was very high (99.95%).

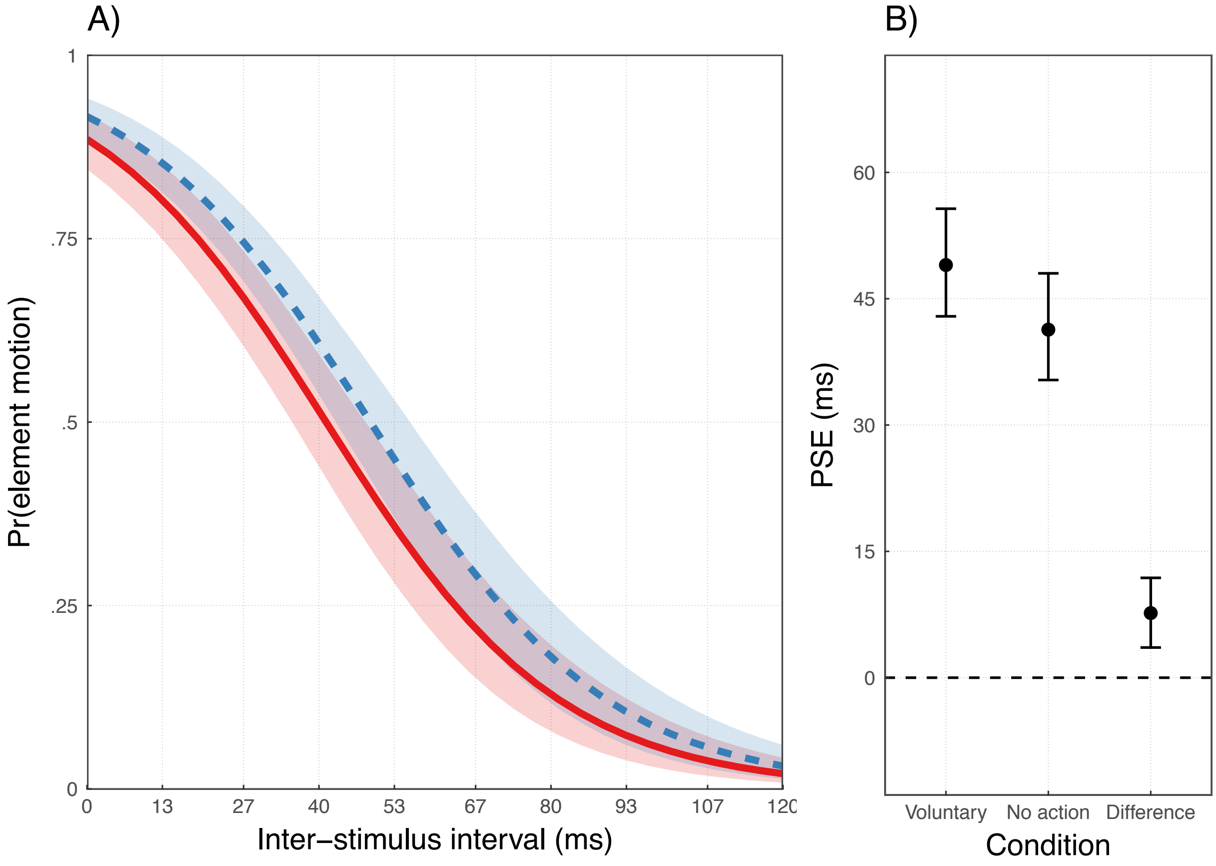

Figure 4. Multilevel logistic regression model of the Ternus display task, Experiment 2a. A) Average model-predicted probabilities of element motion responses for the no action (red) and

voluntary action (blue, dashed) conditions, with 95% CIs as light shades. B) Points of subjective equality in both experimental conditions, and their difference (voluntary action – no action; error bars are 95% CIs).

Discussion

Experiment 2 showed that people were more prone to observe a type of motion (element motion) associated with short ISIs when they voluntarily initiated the display. These results discount the idea that voluntary actions biased or primed participants to report motion, because both possible percepts in the Ternus display are types of motion. Instead, voluntary actions selectively increased the perception of a type of motion associated with short ISIs. However, due to a computer error, the counterbalances were not appropriately rotated across participants. To correct this error, and to replicate our findings, we fixed the counterbalance rotation and conducted a direct replication of Experiment 2.

Experiment 2b

Method

Experiment 2b was a direct replication of Experiment 2 with the computer error in counterbalancing corrected, and using different participants.

Participants. Thirty-eight Columbia University undergraduate students participated in the experiment in exchange for course credit. The experiment was approved by the Columbia University Internal Review Board, and was carried out in accordance with the Psychonomic Society ethical guidelines and with the Declaration of Helsinki.

Results

We used the same exclusion criteria as in Experiment 1: 1 participant was rejected because their element motion responses were not sensitive to changes in the ISI. 1 participant reversed their response buttons, this data was included after reversing the responses.

The results replicated those of Experiment 2: A Bayesian multilevel logistic regression model[1] showed that voluntary actions increased element motion perception ($\hat{\beta}$ action = 0.25, 95% CI [0.002, 0.503], posterior probability = 97.6%, $z = 2.17$, $p = 0.03$). We quantified the perceptual shift using the 50% element motion thresholds (point of subjective equality, PSE). The PSE was 6.3 ms higher in the voluntary action condition than in the passive condition (PSE$_{\text{voluntary}}$ = 50 ms, 95% CI [44, 57]; PSE$_{\text{no action}}$ = 44 ms, 95% CI [35, 53]; difference between PSE (voluntary – no action) = 6.3 ms, 95% CI [0.13, 12.7]). The posterior probability for a positive difference in PSE was high (97.72%).

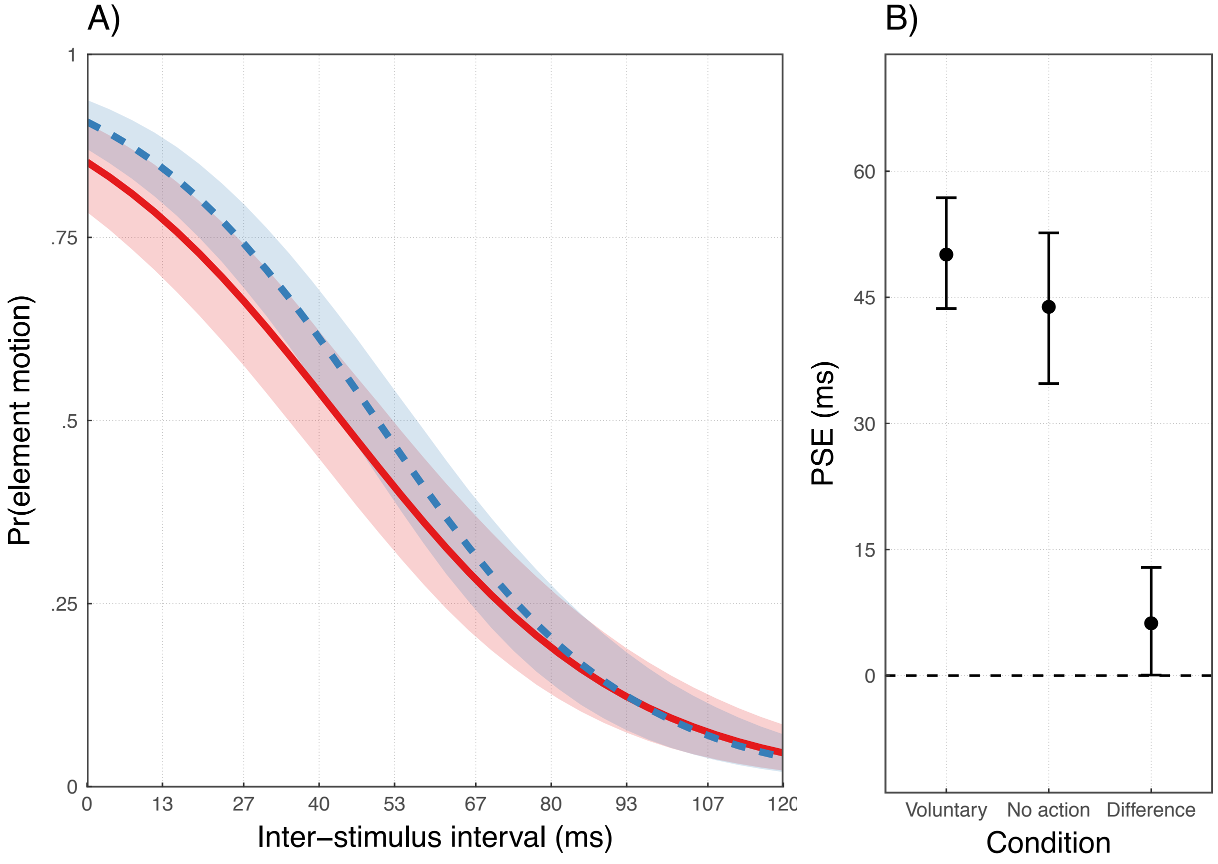

Figure 5. Multilevel logistic regression model of the Ternus display task, Experiment 2b. A) Average model-predicted probabilities of element motion responses for the no action (red) and voluntary action (blue, dashed) conditions, with 95% CIs as light shades. B) Points of subjective equality in both experimental conditions, and their difference (voluntary action – no action; error bars are 95% CIs).

Discussion

Experiments 2a and 2b showed that people observe element motion at longer ISIs following voluntary action versus passive observation. These results support the hypothesis that voluntary actions lead to a perceptual compression of time.

Even so, there remained a possible alternative explanation for the results that implicated differences in people's attention in the two conditions. It is possible that people perceived the stimuli differently between the two conditions not because time was subjectively compressed but rather because voluntary actions allow for better attention, preparation, or ability to predict the timing of the stimuli. For example, previous studies suggest that voluntary actions can have effects on perception because they allow for an accurate prediction of when or what is about to happen (Waszak, Cardoso-Leite, & Hughes, 2012). We thought that attention allocation or differential predictability of the stimuli was an unlikely explanation for the current results. First, increased attention should make the stimuli more distinct. Furthermore, it has sometimes been found that increased attention to a task lengthens, rather than shortens, perceived durations (Macar, Grondin, & Casini, 1994). If that were the case, and if participants were paying more attention in the voluntary action condition they should have seen less apparent motion rather than more apparent motion: the apparent time intervals should have been expanded not compressed. For these reasons we thought that an attention allocation explanation of our results was unlikely.

Nevertheless, increased attention to, preparation for, or predictability of the visual stimuli in the voluntary action condition did seem plausible and the effects of attention in this paradigm were unknown.

To evaluate the differential attentional explanation of our results, we conducted a final control experiment in which we manipulated participants' ability to prepare, attend and predict the stimuli. We employed the manipulations used in classic preparation experiments (e.g. Behar & Adams, 1966) using warning signals to alert participants about an upcoming stimulus, as the basis of our design. In this final experiment, participants observed the Ternus display in two conditions: (1) in the warning signal condition, in which they heard a tone 1 second before the onset of the first visual stimulus, and (2) in the no warning signal condition, in which they were not forewarned about the onset of the visual stimuli. By the attentional view of our effects, the first (warning) condition should be similar to the voluntary action condition and the second (no warning) condition should be like the passive condition. If attention or predictability mediates the effects of action, people should perceive element motion at longer ISIs in the warning condition, than in the no warning condition.

Experiment 3

Method

The stimuli and task were identical to Experiment 2, except that the voluntary action manipulation was replaced with a warning signal manipulation. In the warning signal condition, a tone (600hz sine wave, duration 100ms, clearly audible but not painful volume) was played through the headphones 1 s prior to the initiation of the Ternus display. We chose a 1 second interval between the warning signal and first visual stimulus ('foreperiod') based on previous literature (Behar & Adams, 1966; Langner, Steinborn, Chatterjee, Sturm, & Willmes, 2010), while attempting to minimize cross-modal integration between the warning tone and visual stimulus that could be caused by too short a foreperiod (e.g. Fendrich & Corballis, 2001). In the no warning condition, the Ternus display started after a random delay as in Experiment 2, without any tone.

Participants. Thirty-six Columbia University undergraduate students participated in the experiment in exchange for course credit. The experiment was approved by the Columbia University Internal Review Board, and was carried out in accordance with the Psychonomic Society ethical guidelines and with the Declaration of Helsinki.

Results

We used the same exclusion criteria as in Experiment 1: 3 participants were rejected because their element motion responses were not sensitive to changes in the ISI. 1 participant reversed their response buttons, this data was included after reversing the responses.

The results[1] showed that the warning signal had no effect on perception of the Ternus display ($\hat{\beta}$ warning = -0.03, 95% CI [-0.20, 0.15], posterior probability = 38.4%, $z = -0.36$, $p = .72$). The PSE was 0.5 ms shorter in the warning signal condition than in the no warning condition ($PSE_{warning}$ = 50 ms, 95% CI [43, 58]; $PSE_{no\ warning}$ = 51 ms, 95% CI [43, 59]; difference between PSE (warning – no warning) = -0.5 ms, 95% CI [-3.9, 3.0]). The posterior probability for a positive difference in PSE was very low (38.3%).

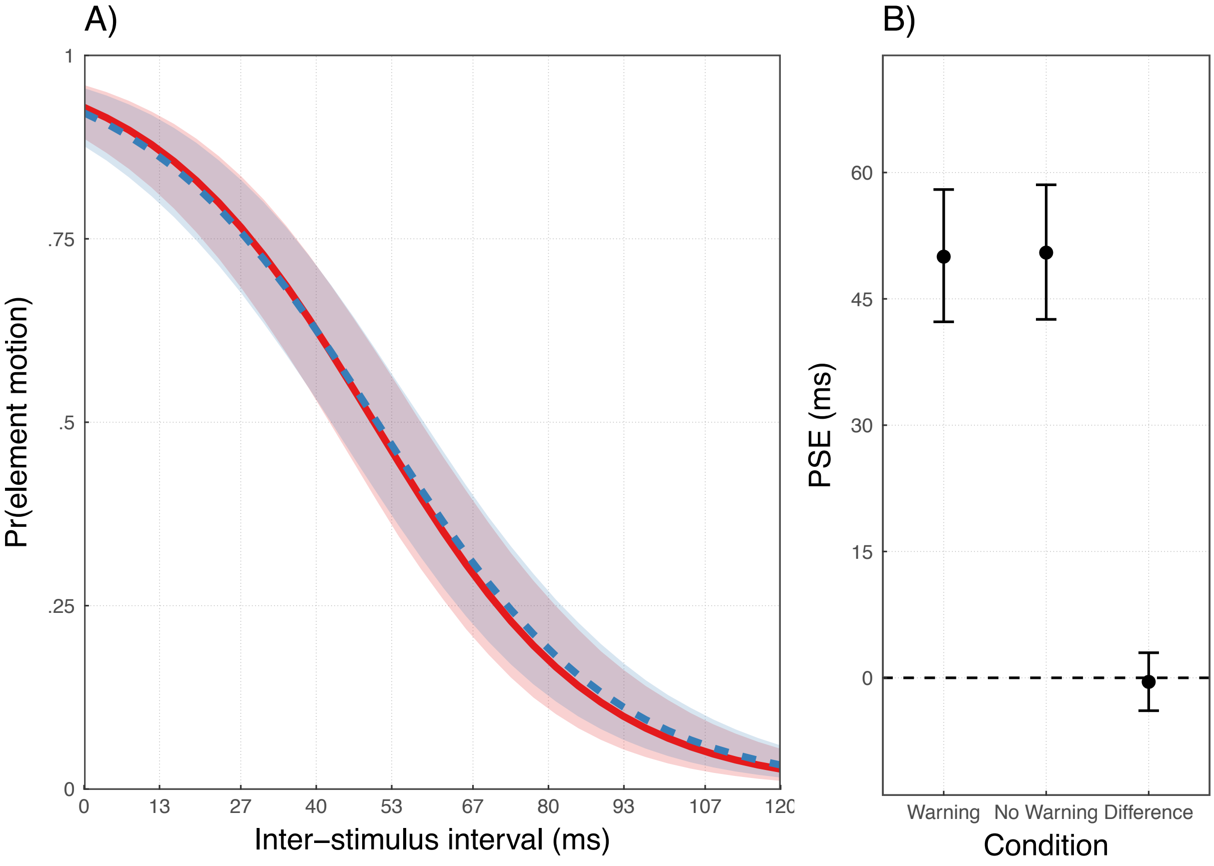

Figure 6. Multilevel logistic regression model of the Ternus display task, Experiment 3. A) Average model-predicted probabilities of element motion responses for the no warning (red) and warning sound (blue, dashed) conditions, with 95% CIs as light shades. B) Points of subjective equality in both experimental conditions, and their difference (warning – no warning; error bars are 95% CIs).

We then asked whether the action and warning signal effects were statistically different from each other by estimating the same model as above, but using all three Ternus experiments' data and including condition by experiment and ISI by experiment interaction terms. This analysis confirmed that the effect of voluntary action was not different across Experiments 2a and 2b ($\hat{\beta}$ = -0.08, 95% CI [-0.36, 0.21]), and that the effect of the warning signal was smaller in Experiment 3 than was the effect of voluntary action in Experiments 2a ($\hat{\beta}$ = -0.38, 95% CI [-

0.67, -0.08]) and 2b ($\hat{\beta}$ = -0.30, 95% CI [-0.59, -0.01]). In summary, these results showed that the warning signal had no effect on participants' perception of the visual illusions, reinforcing the idea that voluntary actions modulated perception of the illusions through changes in time perception, instead of changes in attention, preparation, or predictability of the stimuli.

General Discussion

Experiments 1, 2, and 2b showed that voluntary action produced changes in people's perception of visual motion. In all three cases illusions of motion persisted at longer ISIs following voluntary action than during passive viewing, suggesting that voluntary action compresses subjective time. Although attentional factors can sometimes influence time perception (Ivry & Schlerf, 2008; Zakay & Block, 1996), and it seemed plausible that participants might be paying more attention to the task when they are in the voluntary action condition, Experiment 3 found that helping people attend to the task with an auditory warning signal had no impact on the perception of the visual illusions. Experiment 3 also ruled out another possible explanation for the observed effects. It is possible that actions modulate how their effects are perceived through predictability; that is, actions allow a robust prediction of what is about to happen and when (e.g. Waszak et al., 2012), and therefore the actions may not have been important, but only that the stimuli were predictable. In Experiment 3, a warning sound made the stimuli predictable (in comparison to a no-warning condition), yet had no effect on how the illusions were perceived, showing that the differential perception of visual motion was not due to changes in stimulus predictability alone.

What, then, might cause actions to change how the visual illusions were seen? The main idea that has been forwarded and that is consistent with our data, is that voluntary action compresses subjective time. We will return to this explanation shortly. However, before doing so, there is one other possibility that deserves consideration. It is possible that voluntarily initiated actions pre-activate the perceptual representations of their effects (Hommel, Müsseler, Aschersleben, & Prinz, 2001; Waszak et al., 2012). Participants in the current experiments may have learned to anticipate the second stimulus (Frame 2 in Figure 1) when they initiated the display with a voluntary button press, leading to a pre-activation or a priming of Frame 2. If this occurred, it is conceivable that Frame 2 reached the threshold of conscious awareness faster in the voluntary than the passive condition, and it is this priming that made it appear closer in time to Frame 1.

Although this explanation is possible, it does not easily fit with the findings of Experiment 3. If anticipation alone is sufficient to pre-activate the sensory representation of upcoming events, the warning signal should also have increased perception of element motion. But Experiment 3 did not show such an effect. Perhaps, however, voluntary action entails thinking about, and hence priming, the representation of the effect, whereas external warning signals that reduce temporal uncertainty (Waszak et al. 2012) do not prime the effect. Thus, the voluntary-action related priming account remains a possible explanation of our results. Further, if this account is correct—that voluntary actions pre-activate the perceptual representation of their sensory consequences, thus leading them to reach conscious awareness earlier—our findings would have strong implications for current debates about the possibility of cognitive penetrability of visual perception (e.g. Firestone & Scholl, 2015), because in the current experiments actions did alter participants' perceptual experiences. More research is needed to investigate this exciting possibility.

Finally, we think that the most plausible explanation of the current results is that voluntary action directly altered time perception, resulting in a change in perception that was neither purely retrospective in nature, nor due to attention, or stimulus predictability. Although some have suggested that the intentional binding effect reflects shifts in event timing in relation to one another, rather than a modulation of subjective time itself (Eagleman, 2008; Stetson et al. 2006), it seems more parsimonious to posit that an internal clock mechanism is directly affected. According to this explanation, voluntary actions cause a temporal rate shift in an internal clock. Internal clock models postulate that there is an internal clock that tracks time by generating evenly spaced ticks wherein the number of ticks indicates the magnitude of passed time (see, e.g., Gibbon, Church, & Meck, 1984; Wearden, 2008). Voluntary actions could therefore temporarily slow down this internal clock, giving rise to fewer ticks during the interval which resulted both in shortened judged time and, more importantly, in altered visual illusions of motion.

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