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# Back from the future: Volitional postdiction of perceived apparent motion direction

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ABSTRACT

Among physical events, it is impossible that an event could alter its own past for the simple reason that past events precede future events, and not vice versa. Moreover, to do so would invoke impossible self-causation. However, mental events are constructed by physical neuronal processes that take a finite duration to execute. Given this fact, it is conceivable that later brain events could alter the ongoing interpretation of previous brain events if they arrive within this finite duration of interpretive processing, before a commitment is made to what happened. In the current study, we show that humans can volitionally influence how they perceive an ambiguous apparent motion sequence, as long as the top-down command occurs up to 300 ms after the occurrence of the actual motion event in the world. This finding supports the view that there is a temporal integration period over which perception is constructed on the basis of both bottom-up and top-down inputs.

## 1. Introduction

Among physical events, the future comprises the set of possible states open to a system, whereas the past comprises events that have already happened and which are no longer possible. A system cannot alter its past. If it could, this would have to be a possibility open to the system, which would then paradoxically place the past in the future of the system. Moreover, changing one's own past would be tantamount to self-causation, which is logically flawed because circular.

In contrast, mental events, such as those underlying visual perception, are constructed on the basis of inputs that are sensorily detected over a finite duration. For example, in order to see apparent motion (Kolers & von Grünau, 1976; Ramachandran & Anstis, 1986), there must be a comparison between an object at one location at time 1 and another object at a different location at a later time 2 such that they get bound together over space and time as a single object that moves from position 1 at time 1 to position 2 at time 2. Information about the position of the stimulus at time 1 must have been held online during the duration before stimulus 2 at time 2 appears. Apparent motion thus implies the existence of a perceptual buffer that spans a finite duration of inputs. Stimuli are compared over this finite duration before a commitment is made concerning what happened to give rise to those inputs. The perceived apparent motion path is then, in a sense, a postdictively constructed cover story about what most likely happened to give rise to the sequence of sensory inputs, given the evidence gathered over some finite duration. This perceptual buffer permits the influence of stages of form analysis (Tse, 2006; Tse & Caplovitz, 2006) and expectations (Tse & Cavanagh, 2000) on the construction of motion paths.

Whatever the duration of this perceptual buffer is, it cannot be very long: if it took twenty minutes to construct the perceived motion path of a tennis ball, we would never be able to hit it. On the other hand, in the absence of any duration over which inputs are integrated, no motion sequences could be constructed at all. Evolution presumably created perceptual systems that occupy a "sweet spot" where an adequate processing duration affords the possibility of inferring accurate motion paths constructed on the basis of discretely sampled, noisy and often ambiguous inputs, without taking so long as to make it impossible to respond to rapid events in the world.

Tse and Logothetis (2002) inferred that this buffer lasted at least ~120 ms, given data that form could influence the perception of transformational apparent motion over this duration. Other studies have also suggested that there is a time window during which subsequent inputs can influence the perception of prior inputs. Eagleman and Sejnowski (2000, 2007) demonstrated that the perceived position of a visual stimulus could be influenced by motion signals that occur up to ~80 ms following its appearance. Choi and Scholl (2006) found that the perception of causality could be influenced by contextual motion presented as late as 200 ms after the event. Sergent et al. (2013) reported that an exogenous attention cue presented 400 ms after the presentation could increase the subjective visibility of the stimulus. Kahneman, Treisman, and Gibbs (1992) found that the object-specific

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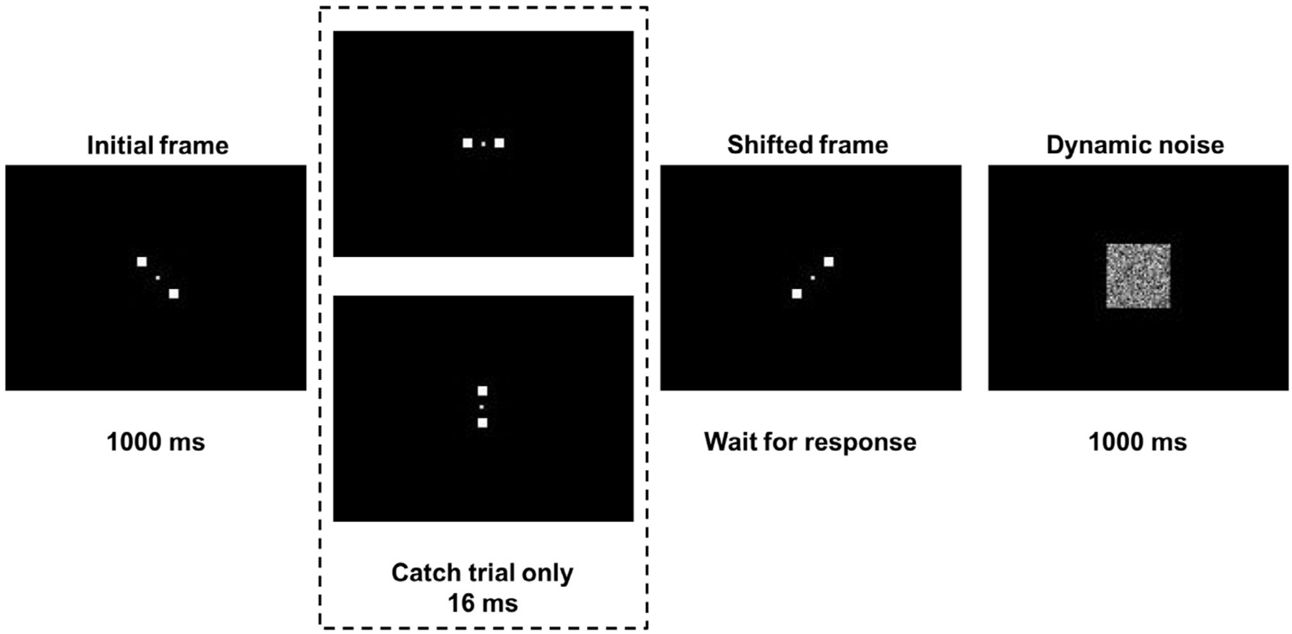


**Fig. 1.** Example of the display sequence. For simplicity, only the central part of the screen is shown and enlarged. The actual stimuli were much smaller, and the size of the black background on the monitor was much larger. From left to right, a typical non-catch trial included an initial frame, a shifted frame (with zero interstimulus time interval between dot positions), and dynamic noise. After the onset of the shifted frame, participants could perceive one-shot apparent motion in either the horizontal or vertical direction. In a catch trial, one of the frames surrounded by the dotted line was added between the initial frame and the shifted frame, in order to make the percept of apparent motion direction unambiguous (e.g. top for vertical motion, bottom for horizontal motion).

preview effect could still be effective 590 ms after the presentation of the preview field.

Given the constructed nature of perception and the fact that this perceptual buffer is of a brief but finite duration, it is possible that a volitionally generated top-down signal could influence how an apparent motion sequence will subsequently be perceived, even if that top-down signal occurs objectively after the completion of the apparent motion sequence in the world. To date no group has tested whether a top-down *volitional* postdictive command is capable of influencing previous ambiguous bottom-up inputs.

In order to test whether such volitional postdiction exists, we modified the paradigm of Mossbridge, Ortega, Grabowecky, and Suzuki (2013). They recruited a one-shot ambiguous apparent motion paradigm to study the time required for volitional control of the perceived direction of motion. They presented two squares, one above and one below fixation. After one second, these were replaced with two horizontally aligned squares with the same eccentricity, one to the right and the other to the left of fixation. Participants could perceive apparent motion as either clockwise or counter-clockwise. A tone presented at a variable time *before* the positional transition instructed participants to voluntarily influence their percept to be clockwise or counter-clockwise. Interestingly, in their study, even when the tone was presented simultaneously with the occurrence of the apparent motion sequence, subjects were able to significantly influence the direction of their perceived apparent motion. We used a similar paradigm to examine whether top-down commands initiated *after* the occurrence of the apparent motion sequence could influence the perceived direction of apparent motion. Since the tone begins at a variable delay after the apparent motion, and because it takes time for the tone to be processed, any ability to influence perceived motion would suggest the possibility of volitional top-down control over the percept of prior inputs.

Two experiments were performed. In Experiment 1, participants tried to influence their perception of apparent motion at several timepoints before and after the physical shift of the stimuli. In Experiment 2, additional timepoints after the positional stimulus shift were included in order to measure how long volitional control can influence the perception of apparent motion.

## 2. Experiment 1

### 2.1. Method

#### 2.1.1. Participants

Forty-seven students (21 males, 26 females; 18–32 years old) from the Dartmouth College community consented to participate in the study for either course credit or monetary reward. The experiment was conducted in agreement with the Code of Ethics of the World Medical Association (Declaration of Helsinki). All participants had normal or corrected-to-normal vision. Participants had to pass two control tests in order to be included for the analysis (see Stimuli and Procedure). Thirty of forty-seven participants (17 males, 13 females; 18–32 years old) passed the first test and twenty-two of those participants (13 males, 9 females; 18–32 years old) passed the second control test. Data from participants who did not pass the first and the second control tests were not analyzed initially (but see Supplementary material for analyses that did not exclude participants).

#### 2.1.2. Apparatus

The experiment was performed in a dark testing room. Stimuli were presented using Psychtoolbox (Brainard, 1997; Pelli, 1997), running in MATLAB (The MathWorks, Natick, MA, USA) on a LCD monitor (15-in, 40.0° × 30.0°, 60 Hz). Participants held their head on a chin rest at a viewing distance of 57 cm. Auditory stimuli were played through a Sennheiser HD 428 headphone (Sennheiser Electronic GmbH & Co. KG, Germany). The calibration of audio to video synchronization was carried out by a Rigol DS1052E digital oscilloscope (Rigol USA, Beaverton, OR, USA) with a customized photodiode device.

#### 2.1.3. Stimuli and Procedure

Each trial began with two white squares (0.44°; 118 cd/m$^2$; CIE xy: 0.351, 0.366) around a white fixation point (0.1°) on a black background (Fig. 1). The centers of the two squares were 0.49° away from the fixation point. Thus the entire apparent motion sequence happened in the foveated zone, within a radius of half a visual degree from the point of fixation. One square was placed to the upper left of the fixation point. The other was placed to the lower right of the fixation point. After 1000 ms, the two white squares shifted to the lower left and the upper right of the fixation point while maintaining the same eccentricity. In this way, participants could perceive the two squares as either moving horizontally or vertically. After the shift, participants pressed a button to report the direction of the perceived motion (horizontal versus vertical; two-alternative force choice, 2AFC). There was no time limit placed on responses. As the response was recorded, a dynamic random noise pattern (1.42°) was shown at the center of the screen for 1000 ms, in order to reduce any hysteresis effect of perception on the next trial.

A pure sine-wave tone, either a high pitch (1480 Hz) or a low pitch (460 Hz) tone, was played for 16 ms at different timepoints before or after the instantaneous shift of two squares to the opposite positions. In the first block of the initial session, participants were told to report the direction of motion they had seen and to ignore the tones played from the headphones. No explanation was given regarding the meaning or the purpose of the tones. This "no-intention" block was used to control for baseline perception bias without volitional control. In the next block, participants were instructed to try to control their perception of horizontal or vertical motion following the respective tones (e.g., high tone indicating 'try to perceive vertical motion,' and low tone indicating 'try to perceive horizontal motion'), with tone meaning counterbalanced between participants. Each participant returned for a second session of two volitional control blocks. Each block contained 160 trials.

There were ten different conditions under both the no-intention and volitional control settings. For eight of the conditions, the auditory tone was played at −533 ms, −133 ms, 0 ms, 16 ms, 33 ms, 67 ms, 133 ms, or 533 ms relative to the onset of the shifted frame (negative times indicate that the tone was played before the shift, positive times indicates that the tone was played after the shift). We also included a condition with no tone played and a control condition involving a catch trial condition (see below). All conditions were presented in random order and counterbalanced for both no-intention blocks and volitional control blocks.

Two control tests allowed us to exclude participants who were not engaged by the task or who did not report what they had actually perceived. Participants were not informed about these criteria. For the first control test, a catch trial condition was introduced with a tone played at −533 ms. In catch trials, two additional white squares (0.44°) were flashed (16 ms) as exogenous cues on the intermediate path of apparent motion (Fig. 1). These squares always appeared along the possible motion path opposite to that commanded by the auditory cue and were intended as a strong, bottom-up visual signal that should overcome the tone-cued direction. Participants who reported the tone-cued direction during catch trials (> 20% of all catch trials) were removed from further analysis, as they could be assumed to not have faithfully reported the motion that they must have actually seen, but instead a motion percept consistent with the auditory command that they had heard. (Note that Mossbridge et al., 2013, did not include such a control, so their data may be contaminated by false reporting of motion percepts).

According to Mossbridge et al. (2013), who used a similar paradigm, participants can influence their percept when the cue is presented 533 ms before the physical stimulus change. For the second control test, in order to make sure participants followed the instruction and actively tried to influence their own percept, they had to achieve above chance (> 50%) proportion of consistent trials when the cue was presented 533 ms before the stimulus change. Only participants who passed both the first and second control tests were included in the analysis reported in the main body of this paper (but see Supplementary material for analyses that did not exclude participants, included for completeness and to allay concerns that anything like data "cherrypicking" was involved).

### 2.2. Results

In order to quantify how well participants could voluntarily control their perception when the auditory cue was presented at different timepoints relative to the physical stimulus change, we computed the proportion of trials in which participants perceived motion in the commanded direction (consistent trials) as a measurement of their volitional control ability. If participants had no control over their perception, the proportion of the consistent trials should not be significantly different from chance level (50%).

For statistical inference, *t*-distributions for data at each timepoint in each setting (no-intention versus volitional control; 2 settings X 8 timepoints = 16 *t*-distributions) were estimated by a bootstrapping procedure (n = 10,000). Specifically, within each condition, the group mean proportion of consistent trials across participants was calculated and then subtracted from each participant's individual data. Then, the chance level (50%) was added to the subtracted data. In this way, all participants' data were centered around the chance level, while the original variance information was maintained. Thus, by bootstrapping across the adjusted proportions and calculating the *t*-statistic within each bootstrapped sample, a *t*-distribution centered around the 50% chance level was generated. The *p*-value was calculated by comparing the original *t*-statistic with this bootstrapped *t*-distribution.

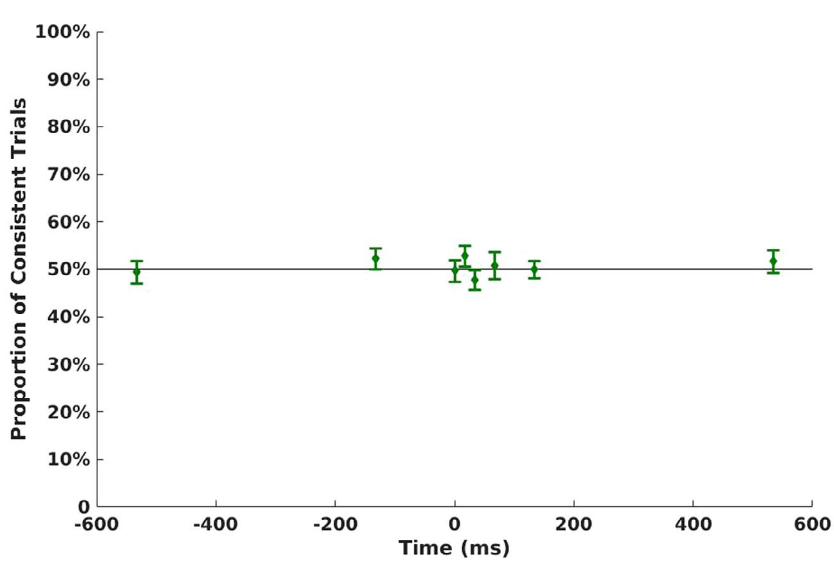


**Fig. 2.** The proportion of trials in which participants' perception was consistent with the direction commanded by the auditory cue for no-intention blocks in Experiment 1. The x-axis represents the time of tone onset relative to the onset of the shifted frame, with negative values corresponding to auditory commands given before the shift. Error bars are standard errors of the mean, adjusted for the repeated measures design. The solid black line shows 50% chance level.

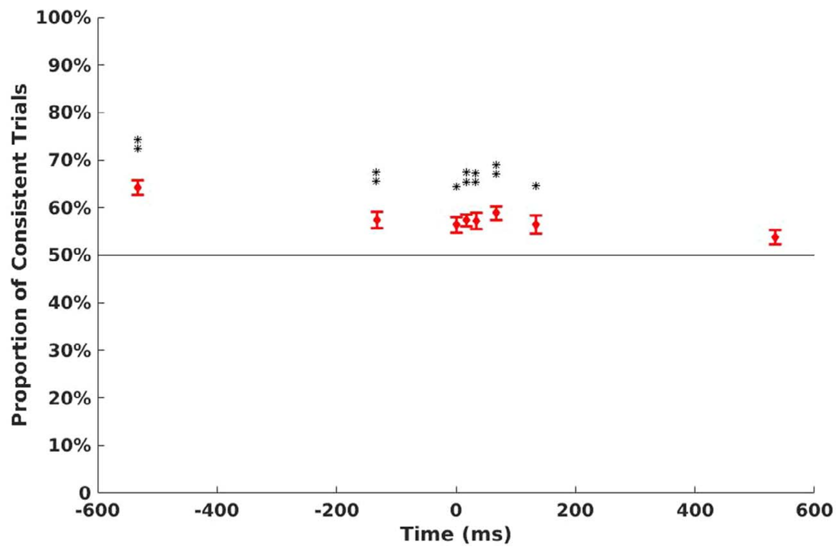


**Fig. 3.** The proportion of trials in which participants' perception was consistent with the direction commanded by the auditory cue for volitional control blocks in Experiment 1. The x-axis represents the time of tone onset relative to the onset of the shifted frame, with negative values corresponding to auditory commands given before the shift. Error bars are standard errors of the mean, adjusted for the repeated measures design. The solid black line shows the 50% chance level. Asterisks indicate significant effects (* = $p < 0.05$; ** = $p < 0.01$).

For the no-intention block, none of the timepoints was significantly influenced by the tones (all $p > 0.250$; Fig. 2), as expected, because during this block the tones had no meaning for subjects. For the volitional control blocks, seven out of eight timepoints tested were significantly influenced by the tone cues (Fig. 3), including −533 ms, −133 ms, 0 ms, 17 ms, 33 ms, 67 ms, and 133 ms (Table 1). When the tone cue was presented 533 ms after the shift of the two squares, participants were no longer able to volitionally influence their perception according to the command given by the auditory cue (Table 1). All *p*-values were corrected for multiple comparisons with a false discovery rate (FDR) of 5% (Benjamini & Hochberg, 1995).

Gengerelli (1948) introduced the apparent motion stimuli we used in this study. He observed that participants saw more vertical motion than horizontal motion. To exclude that such tendency to see vertical motion affected our main result, we calculated the proportion of horizontal and vertical motion reported in our experiment. Since we used a 2AFC response measurement, only the proportion of vertical motion was analyzed. In trials with no tone played (control condition), the proportion of reported vertical motion was not significantly different from chance (50%) in either the volitional control (52.27%, $t(21) = 1.03, p > 0.250$) or no-intention conditions (59.66%, $t(21) = 2.04, p > 0.250$). In trials with cues, the proportion of vertical motion reported was also not significantly different from chance (50%) in volitional control (51.52%, $t(21) = 1.59, p > 0.250$) and no-intention conditions (56.25%, $t(21) = 0.88, p > 0.250$). All *p*-values were calculated based on bootstrapped *t*-distributions (n = 10,000) as described above and corrected for multiple comparison with a FDR of 5%.

Although there was a non-significant tendency to see vertical motion over horizontal motion, this tendency, measured by the proportion of vertical motion reported, was consistent across settings (no-intention versus volitional control; $F(1, 21) = 1.72, p = 0.204$) and conditions (no-tone condition and eight with-tone conditions; $F(8, 168) = 0.87, p > 0.250$). No interaction was observed ($F(8, 168) = 0.80, p > 0.250$) in a two-way repeated measures analysis of variance (ANOVA) test.

**Table 1**
Group Statistics for The Proportion of Consistent Trials by Tone Onset Time (n = 22).

| Onset Time | Mean | $t(21)$ | $p$ | Cohen's $d$ |
|---|---|---|---|---|
| −533 ms | 64.30% | 6.42 | 0.002 | 1.37 |
| −133 ms | 57.48% | 2.97 | 0.005 | 0.63 |
| 0 ms | 56.44% | 3.08 | 0.012 | 0.66 |
| 17 ms | 57.39% | 3.05 | 0.003 | 0.65 |
| 33 ms | 57.29% | 2.96 | 0.005 | 0.63 |
| 67 ms | 59.00% | 4.64 | 0.002 | 0.99 |
| 133 ms | 56.53% | 2.67 | 0.023 | 0.57 |
| 533 ms | 53.88% | 1.73 | 0.129 | 0.37 |

### 2.3. Discussion of Experiment 1

The results of Experiment 1 suggest that a volitional command can influence the perception of apparent motion even if the auditory cue indicating the direction to perceive occurred after the visual event itself. Indeed, even if the start of the auditory cue occurred as late as 133 ms after the actual shift of the stimuli on the screen, subjects could influence what motion direction they would perceive. Therefore, our study extends the original report by Mossbridge et al. (2013), by showing that it is possible to control the perception of apparent motion not only before, but also after the physical shift of the stimuli. The latest timepoints after the shift sampled for Experiment 1 were 133 ms and 533 ms. We found no evidence for volitional control over the percept of apparent motion at 533 ms (Fig. 3). However, it might well be that the volitional command can influence perception later than 133 ms. In order to probe how late the volitional command can influence the perception of apparent motion, we performed Experiment 2 where additional timepoints between 133 ms and 533 ms were sampled. This also allowed us to attempt a replication of these findings.

## 3. Experiment 2

### 3.1. Method

#### 3.1.1. Participants

Another group of sixty-eight students (22 males, 46 females; 17–22 years old) from the Dartmouth College community consented to participate in the study for either course credit or monetary reward. All participants had normal or corrected-to-normal vision. Participants had to pass two control tests in order to be included for the analysis (see Stimuli and Procedure in Experiment 1). Forty-four of sixty-eight participants (16 males, 28 females; 17–22 years old) passed the first control test. Twenty-eight of forty-four participants (11 males, 17 females; 17–22 years old) passed the second control test. Data from participants who did not pass the first and second control tests were not analyzed for data reported in the main body of this paper (but see Supplementary material for analyses that did not exclude participants).

#### 3.1.2. Apparatus

The same apparatus as in Experiment 1 was applied.

#### 3.1.3. Stimuli and Procedure

The design of Experiment 2 was similar to Experiment 1 with the following exceptions. In Experiment 1, the number of trials in the no-intention (baseline) blocks was only one-third of the number of trials in the volitional control condition. Therefore, in order to have the same number of trials in both conditions, participants in Experiment 2 performed two no-intention blocks in the first experimental session and two volitional control blocks in the second experimental session.

Cue timepoints tested in Experiment 2 were −533 ms, −200 ms, −133 ms, 0 ms, 67 ms, 133 ms, 200 ms, and 300 ms. Of particular interest were the timepoints 200 ms and 300 ms in order to test whether the volitional control command can influence perception even after 133 ms.

Instead of the 2AFC design used in Experiment 1, we also included a third possible response “not sure about the percept” in Experiment 2, in order to have a more accurate measurement of participants’ subjective experiences. All other procedures and conditions were the same as in Experiment 1.

### 3.2. Results

Data were analyzed as in Experiment 1. For no-intention blocks, none of the timepoints deviated significantly from chance level (50%; all $p > 0.250$; Fig. 4). For volitional control blocks, the timepoints −533 ms, −133 ms, 0 ms, 67 ms, 133 ms, 200 ms, and 300 ms were significantly different from the 50% chance level after 5% FDR correction (Benjamini & Hochberg, 1995; Table 2, Fig. 5). The number of “not sure about the percept” responses was low (=3.92%, SEM = 0.79%).

As for Experiment 1, we also tested whether participants tended to see more vertical motion than horizontal motion. Since there was a third “not sure” response option in Experiment 2, the proportions of horizontal and vertical motion were compared directly. In trials with no tone played (control condition), the proportion of reported vertical motion was not significantly different from the proportion of reported horizontal motion in either the volitional control blocks (50.56% vs. 46.09%, $t(27) = 0.80$, $p > 0.250$) or no-intention blocks (50.56% vs. 44.98%, $t(27) = 0.98$, $p > 0.250$). In trials with cues, the proportion of reported vertical motion was also not significantly different from the proportion of reported horizontal motion in the volitional control blocks (49.23% vs. 47.95%, $t(27) = 0.39$, $p > 0.250$) and the no-intention blocks (48.01% vs. 47.15%, $t(27) = 0.20$, $p > 0.250$).

Although there was a non-significant tendency to see vertical motion over horizontal motion, this tendency, measured by the difference between two proportions, was consistent across settings (no-intention versus volitional control; $F(1, 27) = 0.004$, $p > 0.250$) and conditions (no-tone condition and eight with-tone conditions; $F(8, 216) = 1.27$, $p > 0.250$). No interaction was observed ($F(8, 216) = 1.73$, $p = 0.093$) in a two-way repeated measures ANOVA test.

**Table 2**
Group Statistics for The Proportion of Consistent Trials by Tone Onset Time (n = 28).

| Onset Time | Mean | $t(27)$ | $p$ | Cohen’s $d$ |
|---|---|---|---|---|
| −533 ms | 65.72% | 7.80 | < 0.001 | 1.47 |
| −200 ms | 53.25% | 1.44 | 0.225 | 0.27 |
| −133 ms | 58.95% | 3.99 | < 0.001 | 0.75 |
| 0 ms | 55.30% | 2.35 | 0.049 | 0.44 |
| 67 ms | 57.45% | 4.12 | < 0.001 | 0.78 |
| 133 ms | 54.26% | 2.13 | 0.073 | 0.40 |
| 200 ms | 57.82% | 4.51 | < 0.001 | 0.85 |
| 300 ms | 55.41% | 2.63 | 0.049 | 0.50 |

### 3.3. Discussion of Experiment 2

In Experiment 2, we tested two more timepoints between 133 ms and 533 ms to explore how late volition can influence the perceived direction of apparent motion, in which the cues were presented at 200 ms and 300 ms after the physical shift of the stimuli. The results suggest that at both timepoints there was a significant influence on the perceived apparent motion direction. We also replicated most of the findings from Experiment 1 and the original results reported by Mossbridge et al. (2013), except at timepoints −200 ms and 133 ms, where no significant influence was found in Experiment 2. However, since effects at neighboring timepoints did replicate, the missing effects at −200 ms and 133 ms could be due to increased noise and might not indicate a functional difference.

## 4. General Discussion

The present study addressed the question whether top-down volition can influence visual perception postdictively. We used an apparent motion ‘quartet’ stimulus, where the perceived direction of motion was ambiguous. Specifically, we examined the influence of top-down control over the perceived motion direction at different time intervals before and after the physical shift of the visual stimuli. In Experiment 1, we found effects of top-down control for various time-intervals *before* the physical stimulus shift, confirming previous reports (Mossbridge et al., 2013). In addition, we report new evidence for an influence of

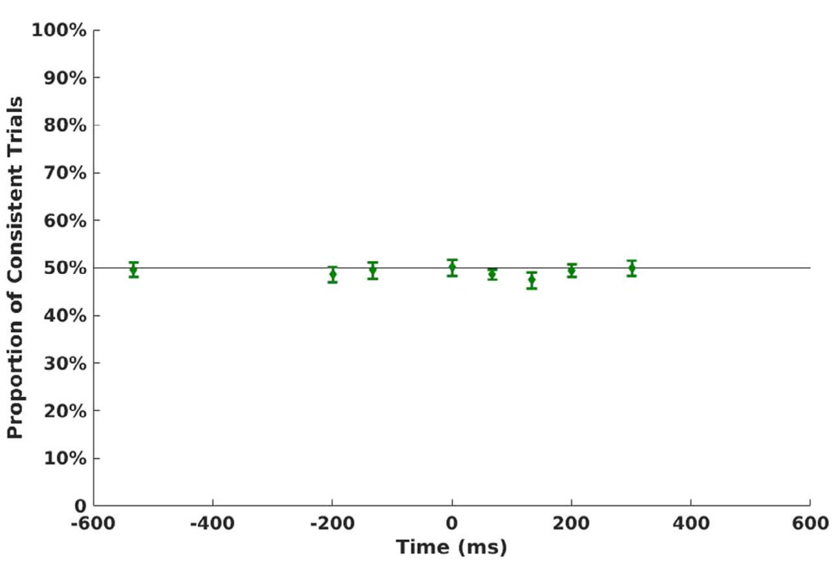


**Fig. 4.** The proportion of trials where participants’ perception was consistent with the direction commanded by the auditory cue for no-intention blocks in Experiment 2. Otherwise same as Fig. 2.

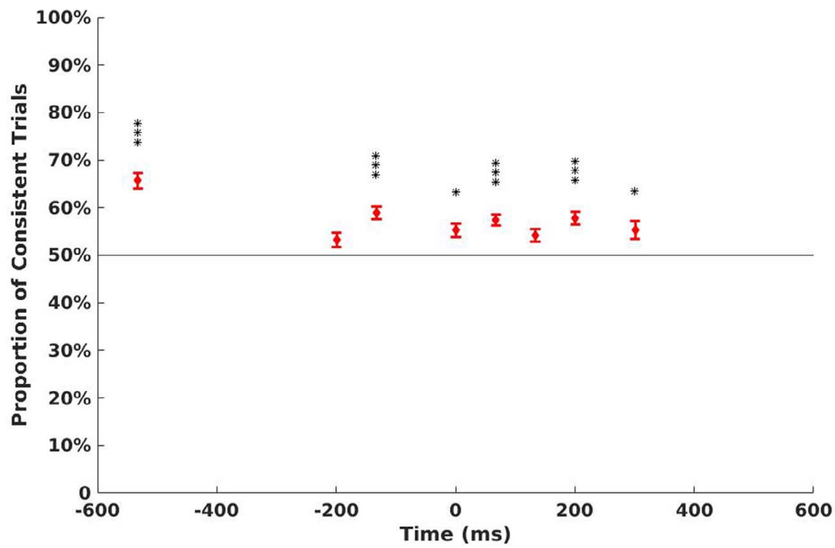


**Fig. 5.** The proportion of trials where participants' perception was consistent with the direction commanded by the auditory cue for volitional control blocks in Experiment 2. Otherwise same as Fig. 3. Asterisks indicate significant effects (* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$).

top-down control on perceived motion direction even 133 ms *after* the physical stimulus shift. In Experiment 2, we replicated most of the findings found in Experiment 1 and extended the results by showing that participants were still able to significantly influence their percept even 300 ms after the physical shift of the stimuli. Overall, our results show that ambiguous sensory inputs can be influenced by top-down control even after the physical event has occurred, suggesting an active construction of visual perception.

The duration of the postdictive integration window of top-down control observed in our study is up to 300 ms following the occurrence of the to-be-influenced visual event. It is longer than the ~80 ms window reported in the motion-induced position shift effect (Eagleman & Sejnowski, 2000), the ~120 ms form analysis window reported by Tse and Logothetis (2002), and the ~200 ms window reported for the contextual effect on causal perception (Choi & Scholl, 2006). It is close to the ~400 ms window for the "retroperception" effect of attention reported recently (Sergent et al., 2013), but shorter than the ~590 ms window for the object-specific preview effect (Kahneman et al., 1992). Such a difference in the durations of integration windows observed in different studies might reflect different stages of visual processing where integration of evidence over a duration happens.

The ~400 ms poststimulus window reported by Sergent et al. (2013) is closest to the integration window we observed here. In their study, an exogenous cue presented 400 ms after the initial Gabor could still significantly increase the subjective visibility of the Gabor. They proposed that poststimulus attention could reactivate a sensory trace retained within the sensory areas and permit conscious access to this trace. In the present study, we extended their finding by demonstrating that poststimulus volitional control could also shape the interpretation of a sensory trace preserved in the sensory areas. Note, however, that our cue likely involves volition, or a volitional process, such as endogenous attention, whereas theirs involved an exogenous cue.

The results in this study are based on subjective reports; therefore, it was necessary to include only participants for the analysis who were engaged by the task and reported exactly what they actually saw. To this end, we used catch trials to exclude participants who might have been reporting the auditory command itself, regardless of their actual visual experience (see control test 1 in Stimuli and Procedure in Experiment 1). In this, we did not follow Mossbridge et al., 2013, because they did not include such catch trials, and therefore may have included data from subjects who reported what they were commanded to see, rather than what they actually saw. We nonetheless replicate their basic findings in the pre-zero timepoint domain, using this more stringent conditionality on inclusion in perceived-motion-direction data.

We also included another test (see control test 2 in Stimuli and Procedure in Experiment 1) to make sure that all participants we included were actively trying to influence their percepts in volitional control blocks, instead of just passively reporting the motion direction; if subjects could not influence their perception in the commanded direction even at timepoint −533 ms, which was the timepoint of a large effect in Mossbridge et al., 2013, then we eliminated them from further data analysis under the assumption that they either were unable to influence their visual perception in a top-down manner or that they did not bother to. Including such subjects in an experiment that examines the timing of the capacity for top-down control of visual perception would only add noise. But see the Supplementary material for analyses that did not eliminate such subjects.

However, one might still argue that the catch-trial test is not enough to purge our data of any spurious influence not due to top-down control; even though this test may have successfully excluded any participants who just reported the direction commanded by the tone, it does not guarantee the absence of a weak response bias. This weak response bias might not be able to overcome the strong non-ambiguous stimuli in catch trials, but still be effective in biasing the ambiguous stimuli used in other trials. The data here cannot fully exclude such bias. But we find the possibility of unaccounted bias unlikely given that we did not observe any significant top-down influence on perceived motion direction at 533 ms post-stimulus (see Experiment 1). If the top-down effect was completely due to such weak response bias, we would have expected to see it presented at all timepoints. The fact that some timepoints did not reach corrected significance suggests that such 'hidden bias,' if exists, is exceedingly weak and unlikely to account for the main body of the top-down effect reported here.

Gengerelli (1948) used the same stimuli as in the current study and found that participants tended to see more vertical than horizontal motion. He concluded this tendency exists because vertical motion happens in the same hemisphere, while horizontal motion involves stimuli moving across hemispheres. The results of our study indicate that each participant's intrinsic tendency to perceive one of the two motion directions, if any, was consistent across the settings (no-intention versus volitional control) and conditions (8 timepoints and no-cue condition), which should have no influence on our interpretation of the main results.

Overall, the results of our two experiments support the conclusion that there is durational window following sensory input, on the order of ~300 ms, during which top-down control can influence the outcome of the interpretive or constructive processes that construct perception on the basis of bottom-up and top-down inputs. Because perception is constructed based on analyses carried out within a perceptual buffer that integrates past inputs over a finite duration, at least in the brain, the future can influence the past postdictively.

## Author contributions

L. Sun, K. C. Hartstein, and P. U. Tse developed the study concept and design. Testing and data collection were performed by L. Sun, K. C. Hartstein, and W. Hassan. L. Sun and S. M. Frank performed the data analysis and interpretation under the supervision of P. U. Tse. L. Sun, S. M. Frank, K. C. Hartstein, and P. U. Tse wrote the manuscript. All authors approved the final version of the manuscript for submission.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.visres.2017.09.001.

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