Subjective control of polystable illusory apparent motion: Is control possible when the stimulus affords countless motion possibilities?

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We investigate whether a new polystable illusion, illusory apparent motion (IAM), is susceptible to subjective perceptual control as has been shown in other polystable stimuli (e.g., the Necker cube, apparent motion quartets). Previous research has demonstrated that, although IAM shares some properties in common with other polystable stimuli, it also has some unique ones that make it unclear whether it should have similar susceptibility to subjective control. For example, IAM can be perceived in a countless number of directions and motion patterns (e.g., up–down, left–left, contracting–expanding, shear, diagonal). To explore perceptual control of IAM, in experiment 1 (*n* = 99) we used a motion persistence paradigm where participants are primed with different motion patterns and are instructed to control (change or hold) the initial motion pattern and indicate when the motion pattern changes. Building on experiment 1, experiment 2 (*n* = 76) brings the method more in line with previous subjective control research, testing whether participants can control their perception of IAM in a context without priming and while dynamically reporting their percepts throughout the trial. Findings from the two experiments demonstrate that participants were able to control their perception of IAM across paradigms. We explore the implications of these findings, strategies reported, and open questions for future research.

Introduction

A well-established phenomenon in polystable stimuli is that it is possible for the viewer to influence how the stimulus appears to them. A defining feature of polystable stimuli is their ambiguity: at times the stimulus may appear one way (e.g., an orientation, a motion direction) and other times the stimulus may appear another way (e.g., a new orientation, a different motion direction). The temporal dynamics of these changes can be influenced by a number of factors including, for example, adaptation (e.g., Hoch, Schöner, & Hochstein,1996; Long & Toppino, 2004; Toppino & Long, 1987), attention (e.g., Kohler, Haddad, Singer, & Muckli, 2008; Stepper, Rolke, & Hein, 2020), expectations (e.g., Davidenko & Heller, 2018), and, as will be the focus of this article, via top–down subjective perceptual control.

Subjective perceptual control has been demonstrated across a broad set of polystable stimuli, including bistable images (e.g., the Necker cube, face-vase) (Peloton & Solley, 1968; Taddei-Ferretti, Radilova, Musio, Santillo, Cibelli, Cotugno, & Radil, 2008; Toppino, 2003; Windmann, Wehrmann, Calabrese, & Güntürkün, 2006), structure-from-motion stimuli (e.g., silhouette spinner, the structure-from-motion sphere) (Brouwer & van Ee, 2006; Graaf, de Jong, Goebel, van Ee, & Sack, 2011; Hol, Koene, & van Ee, 2003; Liu, Tzeng, Hung, Tseng, & Juan, 2012), ambiguous apparent motion (e.g., apparent motion quartets) (Kohler et al., 2008; Mossbridge, Ortega, Grabowecky, & Suzuki, 2013; Ramachandran & Anstis, 1985; Suzuki & Peterson, 2000), and binocular rivalry (e.g., when a house is presented to one eye and a face to the other eye) (Hancock & Andrews, 2007; Meng & Tong, 2004; van Ee, van Dam, & Brouwer, 2005). For many of these polystable stimuli, participants can control what they see to some degree—although to what degree may differ by the type of stimulus and/or instruction (Meng & Tong, 2004; Pastukhov, Kastrup, Abs, & Carbon, 2019;

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van Ee, van Dam, & Brouwer, 2005; Windmann et al., 2006).

Subjective control of ambiguous apparent motion

Since it was first established by Wertheimer (1912) that it is possible to control the appearance of ambiguous apparent motion, a handful of studies have explored the dynamics of this perceptual control in apparent motion quartets. For instance, Ramachandran and Anstis (1983) investigated the global perceptual organization that occurs when multiple apparent motion quartets are presented together and found that when the speed of alternations is higher than three frames per second, it becomes challenging to change between vertical and horizontal percepts. A later study by Kohler and colleagues (2008) explored the control of apparent motion quartets of two different sizes and found a trending effect suggesting that larger apparent motion displays may be easier to control.

Some research has also examined the timing of subjective control in the context of apparent motion displays. Mossbridge and colleagues (2013) explored how quickly it is possible for participants to subjectively control apparent motion quartets by presenting participants with two-frame displays in which there was a variable delay (0–1067 ms) between an auditory cue and the second frame. The authors found that even with a 0-ms delay, participants were able to control how they saw the motion based on the auditory cue, suggesting that subjective control can operate very quickly. Building on this finding, a more recent study by Sun, Frank, Hartstein, Hassan, and Tse (2017) found evidence that even when the auditory cue is presented after the stimulus ($\leq$300 ms after) participants still have the ability to control the motion, even though the stimulus is no longer present. This phenomenon is referred to as *postdictive volition*. This finding suggests that subjective control integrates over a temporal window, rather than in a single moment.

Illusory apparent motion, a new polystable phenomenon

Recently, Davidenko, Heller, Cheong and Smith (2017) reported the discovery of a new ambiguous apparent motion phenomenon called *illusory apparent motion* (IAM). In IAM, ambiguous apparent motion is generated by presenting randomly refreshing pixel arrays across a series of frames at a relatively slow pace (1–3 Hz). IAM offers a large space of possible perceptions of motion patterns (e.g., up–down, up–up, shear motion, contraction–expansion) and directions (e.g., up, down, left, right, diagonal, rotating). It is also possible to introduce nonambiguous apparent motion in IAM displays by having a proportion of the pixels shift coherently in the same direction when transitioning from one frame to the next.

In the first set of studies on IAM, Davidenko and colleagues (2017) sought to restrict the possible interpretations of IAM by priming participants with a series of frames depicting coherent apparent motion that gradually dissolved into a random motion signal. Participants were primed with either *rebounding* (e.g., left–right–left–right) or *drifting* (e.g., up–up–up) apparent motion patterns. During trials, participants indicated with a button press when the initial motion pattern was no longer visible.

To examine patterns of motion persistence, the authors used two measures: (1) the median number of frames following the priming motion after which the button was pressed and (2) the mean proportion of trials in which no response occurred (referred to as no response trials [NRTs]; Davidenko et al., 2017). Both measures revealed a rebounding bias, with significantly longer persistence occurring for rebounding versus drifting motion patterns. In a follow-up study, Heller and Davidenko (2018) suggested that rebounding motion patterns do not simply persist longer, but may actually be a default percept when viewing IAM. When viewing fully ambiguous IAM displays, viewers show a strong bias to see rebounding patterns, even if initially primed with nonrebounding motion.

To date, studies exploring IAM have done so in the context of motion priming tasks, where different parameters of the stimulus (e.g., display type, timing) and/or response type (e.g., indicate when a motion pattern ends, report the perceived direction of motion) have been manipulated. However, anecdotal evidence from presenting IAM to a variety of audiences suggests that IAM can also be disambiguated through verbal priming (Davidenko et al., 2017) and subjective control to see particular directions. In particular, Davidenko and colleagues (2017) report successfully using verbal priming cues, such as “Up! Down!” or “Right! Left!”, to suggest illusory coherent motion to audiences in a classroom setting. In follow-up demonstrations of IAM, audiences have additionally been instructed to try to mentally control the motion by thinking “Up! Down!” or “Right! Left!”, and frequently audience members report being able to successfully control IAM through their mental effort alone.

The current study

As a stimulus, IAM differs in a number of ways from previously studied polystable stimuli. One such way is that other polystable stimuli tend to have a much smaller set of possibilities for disambiguation. For example, the Necker cube and silhouette spinner have only two possible interpretations (front view/top view and clockwise/counterclockwise, respectively) (Liu et al., 2012; Toppino, 2003). Similarly, structure-from-motion cylinders and apparent motion quartets have up to four (clockwise/counterclockwise rotation, two fronts/two backs and vertical/horizontal, clockwise/counterclockwise rotation, respectively) (Hol, Koene, & van Ee, 2003; Kohler et al., 2008). As a maximally ambiguous stimulus, IAM offers the opportunity to build on this past work and explore whether and how subjective control occurs when many more (practically unbounded) interpretations are available.

Thus, the main aim of the current studies is to test whether observers can subjectively control their percepts when viewing IAM. Experiment 1 examines this phenomenon using a persistence task modeled after Davidenko and colleagues (2017) where participants are instructed to try to change or hold a primed motion pattern and to indicate when that motion pattern changes. Experiment 2 tests whether subjective control can be observed in IAM while subjects continuously report their percepts, a method used in previous research with simpler bistable stimuli (e.g., Hol, Koene, & van Ee, 2003; Pelton & Solley, 1968; Kohler et al., 2008; van Ee, van Dam, & Brouwer, 2005). For both of these studies, we predicted that subjects would be able to control their percepts while viewing IAM.

Although there is a robust body of research showing that participants can control their percepts while viewing simple bistable stimuli, it is not altogether obvious whether they should also be able to control their percepts in IAM, because IAM may have unique challenges associated with it. First, owing to the countless number of possible interpretations, participants may have a hard time holding a motion pattern because they are doing so in the face of so many competing interpretations. Additionally, because IAM occurs in a stimulus that is presenting pure noise, for participants to experience any consistent motion, the many possible interpretations of that noise must first be constrained into the desired one. This is unlike other polystable stimuli in which at least one or two of the possible interpretations are perceived for “free” in an automatic, effortless way. This phenomenon presents a unique challenge for IAM because it may be difficult to reconstrain a motion pattern once it is lost. This change could happen any number of times, with potentially different competing motion directions, making it difficult for the participant to adjust or anticipate which motion pattern(s) might compete. In contrast, certain aspects of control may be easier in IAM. For example, participants might find it easier to change a given motion pattern because there are so many more alternative motion patterns for them to select from.

Experiment 1: Motion priming with persistence

Following the methods of Davidenko et al. (2017), participants were presented with a varied number (three, five, or seven) of priming frames that were followed by a series of random IAM frames. Participants self-reported with a button press when the priming motion pattern changed, or did nothing if the priming motion pattern persisted until the end of the trial. Priming frames depicted either rebounding or drifting motion, in a blocked, counterbalanced fashion. To measure subjective control, participants were instructed to either passively observe the motion, change the motion, or hold the motion. In the first two blocks of trials (one with rebounding primes and one with drifting primes, in counterbalanced order), participants were instructed to passively view the motion pattern, and in the two subsequent blocks (again, one with rebounding and one with drifting primes, in counterbalanced order), participants were instructed to change or hold the motion pattern, with instructions changing randomly across trials. Importantly, trials with drifting and rebounding motion patterns were included owing to previous research showing a rebounding bias (Heller & Davidenko, 2018). Including a contrast between these two motion types allowed us to check for experimental demand because there is no a priori reason why subjects should predict that rebounding trials should yield longer persistence.

Methods

Participants

Ninety-nine (mean age, 19.49 ± 1.15 years; female, 57; NB, 1) University of California, Santa Cruz (UCSC), undergraduate students participated. The study was approved by the UCSC Institutional Review Board. Participants gave informed consent and received course credit for participating. All participants had normal or corrected-to-normal vision. The study took approximately 45 minutes to complete.

Stimuli

Stimuli were presented on a 22-inch LCD screen with a 60-Hz refresh rate at a viewing distance of approximately 45 cm. Participants viewed the stimulus without a chinrest. Stimulus creation, presentation, and data collection were done in MatLab using Psychtoolbox-3 (Kleiner, Brainard, & Pelli, 2007). All instructions were presented in 20-point black Times New Roman font on a gray background.

Following the methods of Davidenko et al. (2017), a background array was created using a 560 × 560

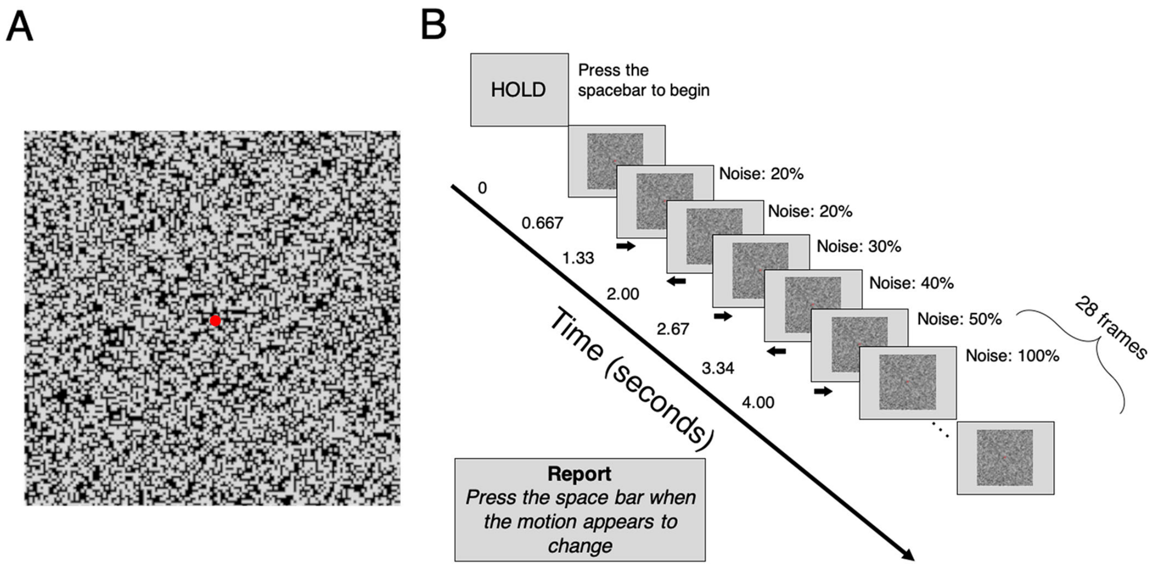

Figure 1. The stimulus and trial sequence used in experiment 1. (A) A single stimulus frame with a red fixation dot. (B) An example trial sequence depicting the hold instruction and five frames priming a horizontal rebounding pattern. During the hold instruction, participants were instructed to try to hold the initial motion pattern for as long as possible. Across an approximately 22-second-long trial, five priming frames, in which the noise level was gradually increased, followed by up to 28 frames of 100% noise were presented. At any point during the stimulus presentation, participants pressed a space bar to indicate when the motion pattern seemed to change from the initial priming motion.

random pixel matrix in which each pixel has a 50% chance of being either black or gray. The fixed background array served as a sampling space for the display array. Display arrays were defined as a 140 × 140 pixel window sampled from within the background array that subtended approximately 9.45° × 9.45° of visual angle (Figure 1A). Participants saw only the display array over a gray background with a red fixation dot placed in the middle. Although other square apparent motion displays, such as apparent motion quartets, require adjustment of the aspect ratio for each participant to override strong biases to see the stimulus in one particular way (Kohler et al., 2008), we used the same 1:1 aspect ratio for all participants. This is because there is no evidence that adjusting the aspect ratio is something that biases the direction of illusory motion in IAM.

During each trial, participants were presented with either three, five, or seven motion priming frames, followed by up to 29, 27, or 25 pure noise frames, such that each trial presented up to 33 frames. This practice amounted to trials that were up to 22 seconds long, depending on participants' responses. There were 48 trials per number of priming frames condition, and they were presented in a randomly interleaved fashion. For the priming frames, a motion signal was generated by shifting the display array (up, down, left, or right) by four pixels with respect to the background array, and randomly refreshing a proportion of the pixels to create a slightly noisy motion signal to mimic the phenomenal appearance of illusory motion in IAM. In trials with three priming frames, 80% of the pixels moved with coherent motion, and in trials with five and seven priming frames, the frames following the first three gradually introduced additional noise at an increment of 10% per additional frame (i.e., coherence decreased from 80% to 70% to 60% to 50%). In the subsequent frames, 100% of the pixels were refreshed randomly, creating a maximally ambiguous, pure noise stimulus. We chose to manipulate the number of priming frames to make it more challenging for participants to anticipate when priming motion frames transformed into random motion frames. The frame rate was 1.5 Hz (i.e., each frame was displayed for approximately 0.667 second (see Figure 1B).

The priming frames were blocked by motion type: Rebounding patterns moved back and forth either in up–down–up–down or right–left–right–left directions. Drifting patterns continued moving in one of four possible directions: up, down, left or right. Within each block, the priming direction was randomized across trials.

Procedure

Participants were presented with one of two possible types of motion prime (rebounding and drifting), and with one of three possible instructions (passive, change, and hold) on how or whether to mentally control the stimuli. Based on the methods of previous subjective control studies (e.g., Kohler et al, 2008, Liu at al., 2012) participants always completed a block of trials with passive instructions first. Henceforth, trials with the passive instruction will be referred to as the *passive block*, because these trials took place before informing participants that they could mentally control the stimuli. Within the passive block, the two types of motion prime (rebounding and drifting) were blocked and the order was counterbalanced across participants.

After the passive block, participants were informed that sometimes they may be capable of mentally controlling the direction of the motion. From this point on, participants were presented with a prompt at the beginning of each trial about how to subjectively control the motion. Henceforth this will be referred to as the *subjective control block*. Within the subjective control block, the type of motion prime (rebounding or drift) was again blocked and the order was counterbalanced across participants, whereas the instruction to change or hold was randomized across trials. This resulted in six types of trials: passive–rebounding, passive–drifting, change–rebounding, change–drifting, hold–rebounding, and hold–drifting. The instruction prompts used in this study were based on Kohler et al. (2008), with the following two modifications: 1) participants were instructed change or hold a motion pattern because rebounding and drift are distinct patterns established across at least two frames, and 2) participants were instructed hold a particular motion pattern (e.g., vertical or horizontal), unlike in Kohler and colleagues (2008), who instructed participants to hold whichever percept was currently dominant.

Before critical trials in the passive–rebounding and passive–drifting conditions, participants were informed that they would be presented with a motion pattern and to press the spacebar when the overall motion pattern appeared to change. To demonstrate what was meant by motion pattern, participants were shown a brief 10-second demonstration of rebounding or drifting motion (according to the motion prime condition) with a clear (90% coherent) motion signal. At the beginning of each motion–prime block, participants were informed whether they would be viewing rebounding or drifting motion patterns. It was then emphasized to participants that if the overall motion seems to change, "for example, to a different direction or a different pattern," to press the spacebar as soon as possible. If the overall motion pattern seemed to stay the same, the participant was instructed to do nothing. Participants were additionally instructed to read the brief intention instruction (e.g., "passively observe the motion") presented before each trial and to keep their eyes fixated on the red dot placed in the center of the stimulus during each trial. Participants then began the critical trials. Each critical trial in the passive block began with the instruction to "passively observe the motion" and a reminder to press the spacebar if and when the motion seemed to change. Participants initiated each trial when they were ready by pressing the spacebar. The passive block consisted of 48 trials (24 per motion prime).

At the beginning of the subjective control block, participants were informed that the random motion they had been viewing can sometimes be mentally controlled. At the beginning of each motion prime block, participants were again informed whether they would be viewing rebounding or drifting motion patterns, and that they would be instructed to change or hold the motion pattern presented. If the instruction was to change the motion pattern, participants were told they should notice the initial motion pattern and then "try to change the overall pattern as soon as possible." If the instruction was to hold the motion pattern, participants were told they should notice the initial motion pattern and then "try to hold the same overall motion pattern for as long as possible." In both cases, participants were instructed to press the spacebar as soon as possible if and when the motion pattern changed. As in the passive block, participants were instructed to read the brief instruction (e.g., "try to [change/hold] the overall pattern as [soon/long] as possible") presented before each trial and to keep their eyes fixated on the red dot placed in the center of the stimulus during each trial. The subjective control block consisted of 96 trials: 24 trials for each type of prime and intention instruction combination.

Results

Two dependent variables were defined for subsequent analyses. The first variable, motion persistence, indicates when participants reported a perceptual change after the initial motion priming frames. First, because there was no pause between the button press to begin the trial and the trial beginning, we removed all trials with a persistence of less than 250 ms, assuming that these trials did not indicate reports of persistence but were accidental double-presses of the key to begin the trial. For descriptive statistics of persistence, we present the mean across participants' median persistence. We elected to use the mean of the medians because persistence distributions tended to be skewed toward earlier frames. The median persistence was obtained for each participant; then, these values were averaged across participants. One limitation of examining only motion persistence is that only perceptual changes that occur during the limited trial time are taken into account. For some instruction types (e.g., change instruction), this measure may be good, but for instructions where persistence is more likely to endure through the end of the trial (e.g., hold instruction), a different measure may be more appropriate. Thus, the second variable examined was the proportion of trials in which there was no response, referred to as NRTs (Figure 2A).

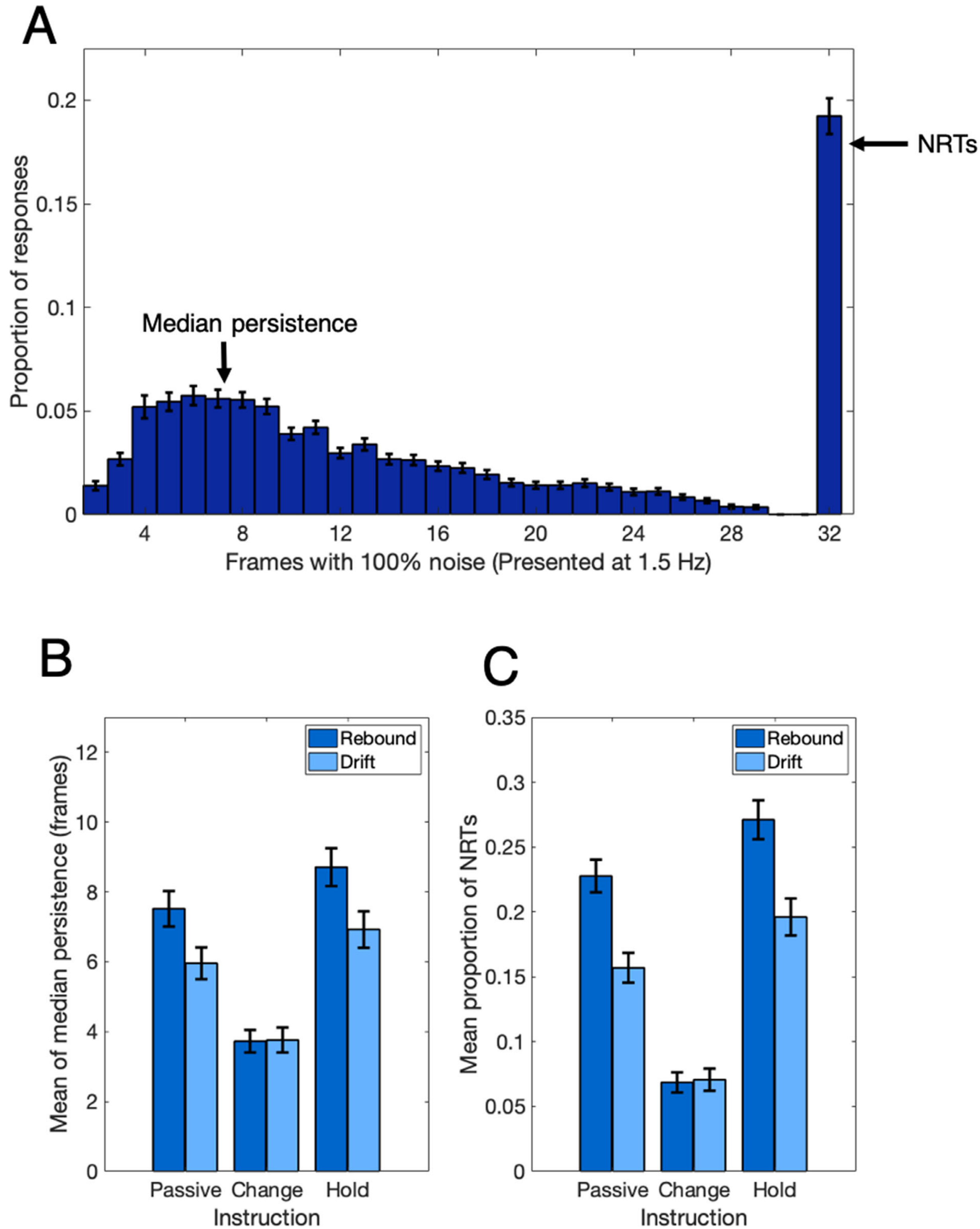

Figure 2. Results of experiment 1. (A) Distribution of motion persistence during pure noise frames, collapsed across motion patterns and priming conditions in the passive block of trials. Each bar represents the proportion of responses on each noise frame indicating when motion persistence of the initial priming frames ended. The bar on the right (labeled 32 on the *x*-axis) indicates the proportion of NRTs, or trials where participants did not press a button to indicate that the initial motion signal had changed—presumably because the initial motion pattern lasted until the end of the trial. The median persistence and NRT arrows on the figure point to the two different measures being used to analyze participants' reports. (B) Mean of median persistence of subjective control collapsed across priming conditions. Change instructions for rebound and drift motion patterns resulted in motion persistence reports occurring on earlier frames compared with hold and passive instructions. Moreover, hold instructions results in reports of longer motion

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persistence compared with passive instructions. Also note that a rebound bias can be observed in the passive and hold conditions, indicated by the motion persistence reports on later motion frames. (C) Mean proportion of NRTs of subjective control collapsed across priming conditions. Change trials for both rebound and drift resulted in a lower proportion of NRTs compared with hold trials. Again note that a rebound bias can be observed in the hold condition, indicated by the larger proportion of NRTs for rebound trials.

Comparing passive and subjective control conditions

First, passive and subjective control conditions were compared in a pair of three-way analyses of variance (ANOVAs). A 3 × 2 × 3 repeated measures ANOVA comparing durations of motion persistence by the number of priming frames (three, five, and seven), type of motion prime (rebound and drift), and instruction type (passive, change, hold) (see Figure 2B) importantly revealed a main effect of instruction such that change instructions has the shortest mean persistence (mean, 3.69 frames; standard error [SE], 0.16), followed by passive (mean, 6.74 frames; SE, 0.22), and hold persistence had the longest mean persistence (mean, 7.66 frames; SE, 0.24), $F(2,196) = 54.15$, $P < 0.001$. There was also a main effect of motion type such that rebounding motion primes (mean, 6.65 frames; SE, 0.19) resulted in reports of longer motion persistence compared with drift motion primes (mean, 5.55 frames; SE, 0.17), $F(1,98) = 14.97$, $P < 0.001$. There was also a main effect of priming frames wherein the fewer priming frames presented, the longer the reported motion persistence (three frames: mean, 6.94 frames; SE, 0.23; five frames: mean, 5.94 frames; SE, 0.22; seven frames: mean, 5.36 frames; SE, 0.21), $F(2,196) = 40.67$, $P < 0.001$. Among the possible interactions, there was a significant interaction between the type of priming frame and instruction, $F(2,196) = 9.61$, $P < 0.001$, reflecting that the effect of motion type (i.e., the rebound bias) was more pronounced during passive and hold instructions compared with change instructions during which there was no rebound bias.

A similar 3 × 2 × 3 repeated measures ANOVA comparing the mean proportion of NRTs by the number of priming frames (three, five, or seven), type of motion prime (rebound and drift), and instruction type (passive, change, hold) (see Figure 2C) also, importantly, revealed a main effect of instruction such that change instructions had the lowest mean proportion of NRTs (mean, 0.07; SE, 0.01), followed by passive (mean, 0.19; SE, 0.01), and hold instructions had the largest mean proportion of NRTs (mean, 0.23; SE, 0.01), $F(2,192) = 41.44$, $P < 0.001$. There was also a main effect of motion type such that rebounding motion primes (mean, 0.19; SE, 0.01) resulted in a greater proportion of NRTs compared with drift motion primes (mean, 0.14; SE, 0.01), $F(1,98) = 19.66$, $P < 0.001$. Among the possible interactions, there was only one significant interaction between the type of priming frame and instruction, $F(2,196) = 11.08$, $P < 0.001$, again revealing that the rebound bias was more pronounced during passive and hold instructions compared with change instructions, which again failed to produce any rebound bias.

As mentioned in the Methods, the purpose of manipulating the number of priming frames was to make it harder for participants to anticipate when the motion primes transformed into random motion. Because the number of priming frames was not a main variable of interest and it showed no interactions in these analyses, we chose to collapse across the number of priming frames for the subsequent analyses. We ran a series of 2 × 2 ANOVAs comparing each pair of different instructions (change versus hold, passive versus change, passive versus hold) and each type of motion prime (rebound versus drift). We did this separately for the persistence and NRTs measures which resulted in a total of six 2 × 2 ANOVAs. The results from the persistence analyses revealed a consistent main effect of instruction (all pairwise P values < 0.005) and the type of motion prime (all pairwise P values < 0.05). Similarly, the results from the NRTs analyses revealed a consistent main effect of instruction (all pairwise P values < 0.05) and the type of motion prime (all pairwise P values < 0.05). Additionally, for both persistence and NRT measures, there was an interaction such that the rebound bias was greater during hold and passive instructions compared with change instructions (all pairwise P values < 0.001) (see Figures 2B and 2C).

Discussion

Importantly, the significant main effect of instruction type across the persistence and NRT measures demonstrates that participants are able to control their percepts while viewing IAM, even with its many possible interpretations. Further, comparisons between the two subjective control instructions and the passive instructions suggest that participants were able to control motion percepts in two ways. Compared with durations of motion persistence during passive instructions, participants were able to 1) increase the duration of a motion percept when instructed to hold and 2) decrease the duration of a motion percept when instructed to change. Importantly, participants seem to be much more successful at reducing their persistence in the change relative to the passive condition (a decrease of 45.3%), compared with increasing it in the hold relative to the passive condition (an increase of

13.7%). This finding suggests that the primary way that participants controlled their percepts in experiment 1 was by actively changing, rather than holding, their percepts.

In addition, the results replicate two previous findings from Davidenko and colleagues (2017, 2018). First, fewer priming frames tended to result in longer persistence, even when participants were trying to control their percepts. This effect was found for both measures in the passive condition and for the persistence measure in the subjective control condition, and is consistent with previous findings (Heller & Davidenko, 2018). Second, a rebounding bias was found in which rebounding motion primes led to longer persistence compared with drifting motion primes. This effect was found in the passive and hold instruction conditions and in both measures; however, it failed to appear in the change instruction condition.

Experiment 2: Subjective control with dynamic report of percepts

Experiment 2 tests subjective control in the absence of priming frames. Experiment 2 brings our methodology more in line with previous work (e.g., Kohler et al., 2008; Hol, Koene, & van Ee, 2003; Pelton & Solley, 1968; van Ee, van Dam, & Brouwer, 2005) and tests whether it is still possible for participants to control their percepts while viewing IAM with a more complex task. In particular, participants are instructed to try to perceive specific motion patterns and report throughout the trial the type of motion that they perceive.

Changing the way that participants report their percepts was the main change made to bring IAM in line with previous methods. However, additional changes were made to the design (from experiment 1) to streamline the experiment and include catch trials. First, because experiment 1 demonstrated a greater proportion NRTs for rebounding instructions, suggesting that it was easier for participants to control rebounding compared with drift motion patterns, experiment 2 asks subjects to attempt to perceive different directions (vertical or horizontal) of rebounding motion only. In addition to considering only rebounding motion, experiment 2 also excludes the passive instruction included in experiment 1, focusing on the contrast between change and hold instructions. Excluding passive instructions allowed the experiment to be designed more efficiently, focusing on the main research question and allowing additional measures (including eye tracking and a follow-up survey). In addition, we included catch trials (described elsewhere in this article) to ensure participants were reporting their actual percepts rather than simply reporting the instructed motion.

Methods

Participants

Seventy-six (mean age, 20.02 ± 1.70 years; female = 39) UCSC undergraduate students participated. The study was approved by the UCSC Institutional Review Board. Participants gave informed consent and received course credit for participating. All participants had normal or corrected to normal vision. The study took approximately 30 minutes for participants to complete.

Stimuli

Stimuli were presented on a 22-inch screen with a 60 Hz refresh rate at a viewing distance of approximately 77 cm. Stimuli were created and presented in MatLab using Psychtoolbox-3, and data were collected with MatLab software (Kleiner, Brainard, & Pelli, 2007). Instructions were presented in a black font on a light gray background. Participants had their chin placed in a chin rest for the stimulus presentation portion of the study.

IAM stimuli were created with a method similar to experiment 1, but with the following changes. First, the stimulus was larger, subtending approximately 12.61° x 12.61°, and included a circular gray fixation region that subtended approximately 3.67° in diameter (Figure 3A). In addition, there were no priming frames. Instead, during each of 24 trials, participants were presented with 15 frames with 100% randomly changing pixels. This resulted in each trial lasting for 10 seconds (Figure 3B). Finally, to check for experimental demand, we included 6 additional trials that contained nonambiguous directional apparent motion throughout all 15 frames. In these catch trials, the motion signal level was set to 80%, which produces a readily perceptible motion signal. One-half of the catch trials depicted vertical (up–down) rebounding motion and the other half depicted horizontal (left–right) rebounding motion. As in experiment 1, the same 1:1 stimulus aspect ratio was used for all participants.

Procedure

Participants began the study by being informed about vertical and horizontal motion. For the purposes of this study, vertical motion was defined as an up–down rebounding motion pattern and horizontal motion was defined as a left-right rebounding motion pattern. A brief (8-second) demonstration of each motion type with 100% motion signal was presented to participants to clarify the descriptions of the motion

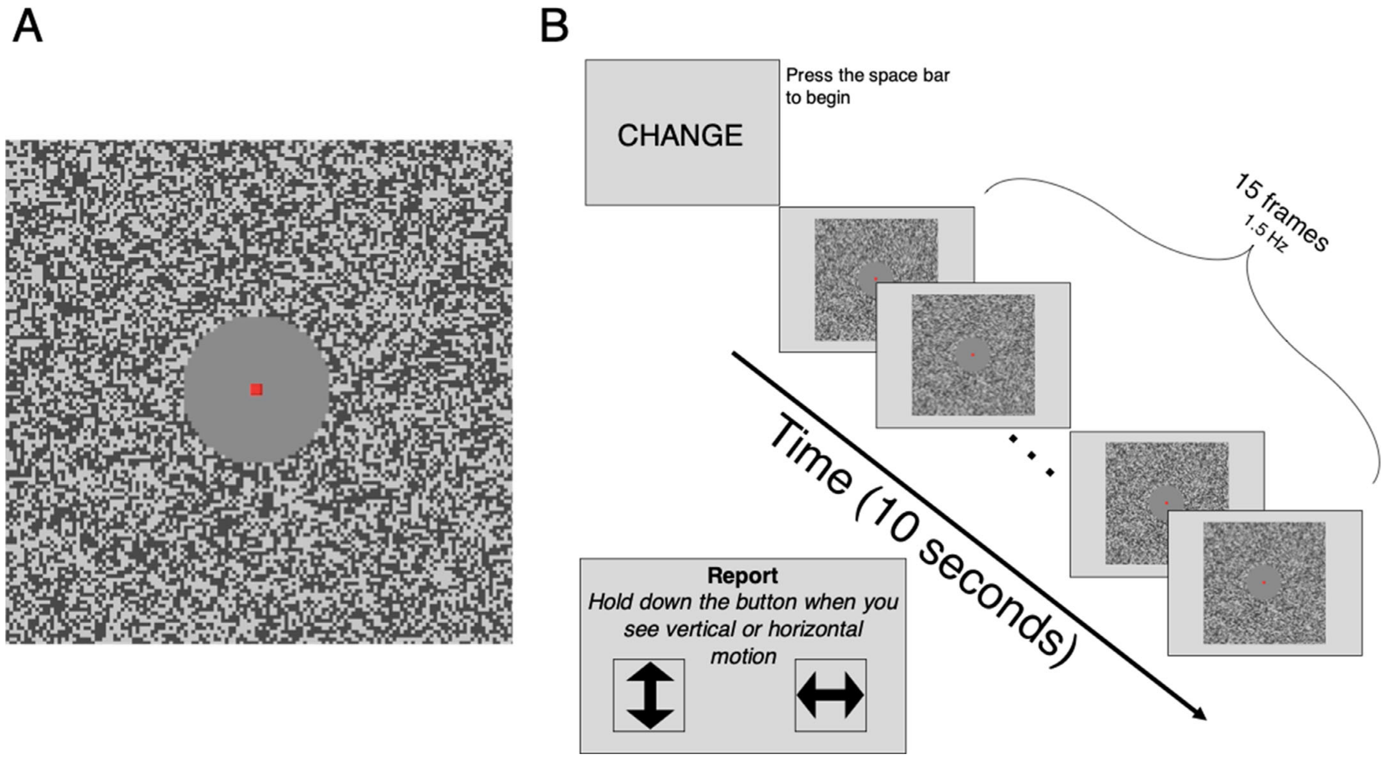

Figure 3. The stimulus and trial sequence used in experiment 2. (A) A single stimulus frame with a fovea mask and red fixation dot. (B) An example trial sequence depicting the change instruction. During the change instruction, participants were instructed to change from a horizontal rebounding to a vertical rebounding pattern as quickly as possible. Across a 10-second trial, 15 frames of 100% noise were presented, and participants held down one of two buttons to report when they were perceiving vertical or horizontal rebounding motion patterns.

patterns. Participants were instructed to report their perceptions of vertical and horizontal rebounding motion during the study by holding down one of two keys. To report vertical motion, participants were to hold down, using their left index finger, the *d* key which had an up–down arrow icon overlaid on the key and to report horizontal motion, participants were to hold down, using their right index finger, the *j* key which had a left–right arrow icon overlaid on the key. During times where participants perceived neither vertical or horizontal motion, participants were instructed to not hold down any key. To ensure participants understood the instructions for reporting motion percepts, they completed four practice trials. The practice trials contained different combinations of vertical and horizontal motion patterns as well as a diagonal motion pattern (to check that subjects also knew to release both keys if they perceived anything other than vertical or horizontal motion).

After the practice trials, subjects were informed that the stimuli they would be shown during the study can sometimes be controlled mentally. Participants were also informed that a prompt instructing them to either 1) "change between vertical and horizontal motion patterns as quickly as possible," 2) "hold a vertical motion pattern for as long as possible," or 3) "hold a horizontal motion pattern for as long as possible" would be presented before each trial. For all of the critical trials ($n = 24$), each of these instructions was presented eight times and were presented in random order. This, combined with the six catch trials (detailed elsewhere in this article), resulted in 30 total trials in the experiment. Participants self-initiated each trial by pressing the spacebar. Importantly, to control for the possible influence of eye movements, participants were instructed to maintain fixations within the gray fixation region. Participant eye movement data were collected (see Eye tracking section).

Catch trials

For catch trials, the prompt to change the motion pattern was always presented along with a stimulus composed of 80% motion signal. The motion presented could either be rebounding vertical motion or rebounding horizontal motion to match the possible types of motion that participants could report perceiving (as mentioned elsewhere in this article). Catch trials always included the instruction to change the motion while actually showing consistent rebounding motion (either vertical or horizontal) throughout the trial. The reasoning behind this was based on the work of Kohler and colleagues (2008), who reported that participants found the change condition to be more effortful for apparent motion quartets. Although it remains unclear whether apparent motion quartets and IAM are related, our catch trials were based on the assumption that change instructions may also prove to be more effortful than hold instructions for IAM displays without the aid of priming frames. If changing is more effortful than holding, then the change instruction should be better at ascertaining whether participants are engaged with the task. Importantly, there was a question included in the end of experiment survey that asked participants whether they found change or hold more challenging. As it turned out, results from the survey showed that most participants who responded to this question indicated that holding IAM was easier than changing it (31 of the 43 participants), suggesting that the change trials, as we hoped, should be the more effortful instruction. Catch trials were presented randomly interleaved with critical trials.

Eye tracking

During critical trials, eye movement data was collected. We used a GazePoint Eye Tracker with 60 Hz sampling frequency and 1.0 to 1.5 degrees of accuracy. First, for analyses that were conducted to assess participants' time spent fixating (which is used as a threshold criteria for inclusion to the data set), screen recordings superimposed with the interpolated fixation positions were analyzed during the middle 8 seconds of each trial. The middle 8 seconds of each trial were analyzed to exclude times when participants' eye movements may have been orienting during the first second of the trial and times when eye movements may reflect anticipation of the trial ending. The fixation region of interest was the same for all trials. However, the timing of fixations was controlled by each participant self-pacing through the study. Once each of these trial periods was defined, eye movement data was analyzed using MatLab.

For the primary analysis of eye movements, we examined participants' saccades. Saccadic eye movement data were analyzed after eliminating the first and last five frames of each trial (amounting to 83 ms removed from the beginning and end of each trial), leaving the middle 9.83 seconds of each trial. The middle 9.83 seconds of each trial were analyzed, again, to exclude times when participants' eye movements may have been orienting during the first moments of the trial and times when eye movements may reflect anticipation of the trial ending. All of these analyses were conducted using MatLab.

Survey

Once participants completed the critical trials, they then completed a survey that consisted of six or eight questions, depending on whether subjects indicated that they did (eight questions) or did not (six questions) use strategies. The survey included yes or no and open-ended questions about whether participants happened to use any strategies during the experiment, and, if so, which strategies participants used to control the motion under different instruction conditions (i.e., change versus hold). For the purposes of this article, we present data only for questions 2 and 3 of the survey. Question 2 asked participants to report their strategies when attempting to change the direction of the motion, and question 3 asked them to report their strategies when attempting to hold the direction of the motion. Both questions involved open-ended short answer responses in which participants reported whatever they wanted. (See Appendix for all survey questions.)

Behavioral data analysis

Participants reported their percepts by pressing one of two buttons throughout a 10-second trial. The main measure we used, the mean button press duration, was obtained by collecting individual percept durations within a trial, then taking an average duration for each trial. This calculation was done within each instruction (i.e., change, hold vertical, hold horizontal) and perceptual state (i.e., vertical and horizontal) combination for each participant. To supplement the mean button press duration measure, we also report the mean number of button presses per trial for each instruction and perceptual state combination.

Concerning catch trials, a good performance on catch trials is indicated by a participant holding down a button consistent with the actual motion (e.g., report perceiving vertical when vertical motion was presented) that was shown throughout the 10-second trial, regardless of the change instruction. The analysis for determining catch trial outliers was based on a threshold to define participants who were not adhering to the task. The threshold was determined by first calculating the amount of time that participants reported 1) percepts consistent with and 2) percepts inconsistent with the motion presented in the catch trial. Then we required that participants correctly report the consistent motion for 2 seconds longer than the inconsistent motion, indicating that they were performing above chance, to be included in the dataset for analysis.

As mentioned in the Methods, the choice of including only change instructions for catch trials was based on Kohler and colleagues' (2008) report that participants found the change trials to be more effortful, although it is not clear to what extent this would also be true of IAM. Question 5 of the postexperiment survey asked participants "Did it seem easier to CHANGE or HOLD the motion? Please briefly describe." Most participants who responded to this question (31 of the 43) indicated that holding IAM was easier than changing it, suggesting that the change trials, as we hoped, should be the more effortful instruction.

Survey data analysis

The survey analysis will focus only on questions 2 and 3 (see Appendix). As mentioned elsewhere in this article, participant responses to the survey were open ended, and these open-ended responses were coded by independent coders for analysis. First, several categories of data were developed based on the types of strategies participants seemed to be reporting in their responses: 1) no strategy indicated, 2) rhythmic bodily movements (i.e., non–eye-based bodily movements), 3) eye movements, 4) mental imagery (including nonvisual imagery), 5) attention, and 6) other (i.e., anything not captured by the first five categories). For the no strategy category, coders were instructed to include participants who reported that they used no strategy and participants who left the question blank. For the rhythmic bodily movements category, coders were instructed to include any rhythmic bodily movements, excluding eye movements, into this category. For example, participants who indicated subtle motor movements with their fingers or breathing patterns were to be categorized as using rhythmic bodily movements as a strategy. For the eye movement category, coders were instructed to include responses explicitly mentioning eye or gaze movements into this category (e.g., looking from left to right). For mental imagery, coders were instructed to include responses where participants seemed to be using imagery associated with any modality (e.g., visual, auditory, or motor). For example, participants who reported thinking the words up–down–up–down in their mind would be categorized as using mental imagery. For the attention category, coders were instructed to include responses where participants report using any type of attention, including, for instance, covert attention or spatial attention. Coders were instructed to code any responses that were uncategorizable into the other category. In some cases, participants reported using more than one strategy per instruction type. For these cases, coders were instructed to try to categorize the response based on which strategy seemed to be most prominent. Using this set of categories and instructions, three coders (including coauthor M.J.) who were aware of the purpose of the experiment coded each response into one of the six listed categories.

Intercoder reliability was calculated using Krippendorf's alpha ($K\alpha$) (Hayes & Krippendorf, 2007; Krippendorf, 2008, 2011). $K\alpha$ is used in content analysis to measure reliability based on the degree of rater disagreement. Alpha scores can range from –1 to 1 where scores closer to 1 indicate perfect agreement and scores closer to -1 indicate perfect disagreement. A score of approximately 0 indicates no relationship (or random) agreement among raters. The $K\alpha$ was calculated using a freely available MatLab function (Eggink, 2021). The reliability of coders agreement for questions 2 and 3 was a $K\alpha$ of 0.68, which is above the acceptable minimum for the $K\alpha$ (De Stewart, 2012).

To see how the reliability of our coders compared with the range of possible random responses, we ran a simulation based on randomizing the responses of each of our coders to capture what it would look like if that particular person were simply coding randomly. Once each individual's ratings were randomized, they were recombined with the scores of the other three coders to generate a new $K\alpha$. This simulation was run 1,000 times, generating 1,000 $K\alpha$ values. The minimum reliability score generated was a $K\alpha$ of –0.11 and the maximum reliability score was a $K\alpha$ of 0.09. This process helps to demonstrate that the actual $K\alpha$ reliability achieved ($K\alpha = 0.68$) is well above what it would have been had our coders simply been categorizing responses randomly.

The final categorization of the data was determined by at least two coders being in agreement about the category. Responses that did not receive two out of three coders agreement were excluded from further analysis.

Results

Subjective control of IAM

Of the 76 participants, 20 were not included in the following analysis. Eleven participants were removed for not meeting the threshold for catch trial performance (as detailed elsewhere in this article); 4 participants were excluded because they did not press any buttons during the entire study, suggesting that they either could not see coherent vertical and horizontal motion, they were not engaged in the task, or did not understand the instructions; and 5 participants were excluded for reporting an excessive number of reversals (an average of more than 15 reversals per trial, which exceeded the maximum possible given the number of frames in the stimulus across the 10-second trial) during the change condition or catch trials, suggesting they may not have understood or followed the instructions.

For change trials, the mean of button press durations was 3.34 seconds (SE, 0.23) for vertical percepts, whereas the mean button press duration was 2.96 seconds (SE, 0.21) for horizontal percepts. For trials where participants were instructed to hold vertical motion, the mean button press duration was 5.01 seconds (SE, 0.32) for periods where participants

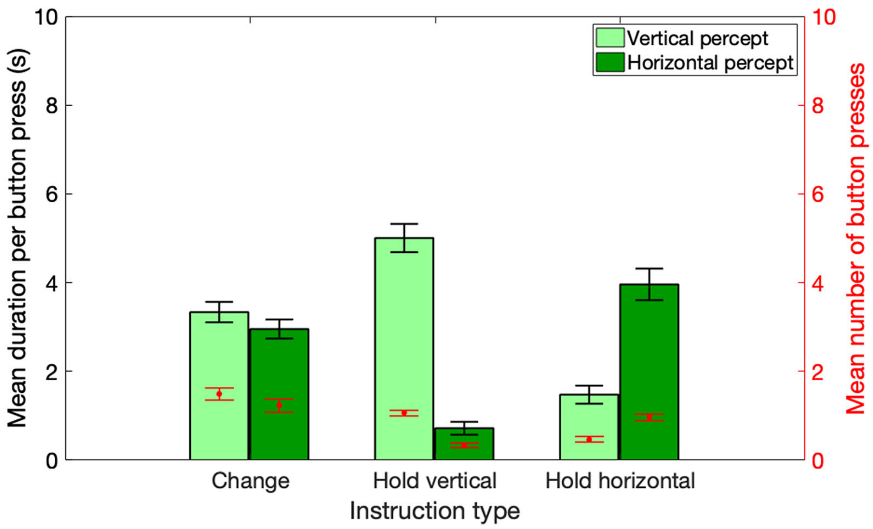

Figure 4. Results for experiment 2. The mean button press durations and the mean number of button presses for each instruction type (change, hold vertical, hold horizontal) and perceptual state (vertical, horizontal) show longer button press durations for percepts consistent with the hold instruction (e.g., vertical percepts when instructed to hold vertical) compared with change durations, indicating that participants can control their perception of IAM.

perceived vertical motion (consistent with the instruction) and 0.72 seconds (SE, 0.15) for periods where participants perceived horizontal motion (inconsistent with the instruction). For trials where participants were instructed to hold horizontal motion, the mean button press duration was 3.96 seconds (SE, 0.36) for perceiving horizontal motion (consistent with the instruction) and was 1.48 seconds (SE, 0.20) for perceiving vertical motion (inconsistent with the instruction; Figure 4). To supplement the analysis of mean button press durations, we also examined the mean number of button presses (Figure 4). In general, the mean number of button presses shows the same overall pattern of results as the mean button press durations.

A 3 × 2 repeated measures ANOVA comparing the mean button press durations by instruction type (change, hold vertical, hold horizontal) and perceptual state (vertical, horizontal) revealed a main effect of perceptual state, $F(2,55) = 15.17$, $P < 0.001$, where the vertical percepts tended to last longer than the horizontal ones. In addition, there was an interaction between instruction type and perceptual state, $F(2,55) = 74.11$, $P < 0.001$. To further explore the interaction revealed in the 3 × 2 repeated measures ANOVA, we followed up with a 2 × 2 repeated measures ANOVA comparing hold instructions (hold vertical, hold horizontal) and perceptual state (vertical, horizontal). There was a similar main effect of the type of percept, $F(2,55) = 17.15$, $P < 0.001$, owing to longer button press durations for vertical percepts. Importantly, there was a strong interaction, $F(2,55) = 79.27$, $P < 0.001$, where motion that was consistent with the instruction had longer durations than motion that was inconsistent with the instruction.

We also examined whether participants controlled their perception of motion in hold instructions by increasing the duration of desired percepts, by decreasing the durations of the undesired percepts, or a combination of both. To examine how participants controlled their percepts, the first and last (if it coincided with the end of a trial) button presses were removed. Then, because 10 seconds trials are not long enough to analyze button presses on a by-participant basis, we instead collected button presses for each instruction condition (change, hold vertical, and hold horizontal) and percept type (vertical and horizontal) combination, and examined all of the button press durations for each instruction-percept combination aggregated across participants.

First, an independent samples *t* test comparing the button press durations for change instruction trials with button press durations for hold instruction trials consistent with the instructed motion (e.g., when participants are instructed to see vertical and they report seeing vertical) revealed that durations for consistent hold button presses (mean, 3.33 seconds; SE, 0.15) were longer than button presses in the change condition (mean, 2.69 seconds; SE, 0.05), $t(952) = 5.00$, $P < 0.001$. Then, a second independent samples *t* test comparing the button press durations for change instruction trials with inconsistent button press durations with button press durations for hold instruction trials inconsistent with the instructed motion (e.g., when participants are instructed to see vertical and they report seeing horizontal) found that the durations for inconsistent hold button presses (mean, 2.32 seconds; SE, 0.14) were shorter than button presses in the change condition (mean, 2.69 seconds; SE, 0.05), $t(952) = 2.70$, $P = .007$. Collectively these results suggest that participants were able to hold the motion both by increasing the duration of the desired percept and by shortening the duration of the undesired percept. Additionally, the mean difference between change and consistent hold trials was 0.64 ± 0.61 seconds, but was 0.37 ± 0.27 seconds for change and inconsistent hold trials, suggesting that the influence of seeing the desired percept when holding had a greater effect.

Eye movements

Of the 56 participants included in the behavioral analysis, we were able to analyze the eye tracking data for 35 participants. We applied two threshold criteria where participants needed to have 1) 60% of usable eye movement data and 2) fixation performance for longer than 11% during critical trial times to be included into the analysis. For the first criterion, 16 participants were removed, which occurred owing to artifacts, protocol errors (e.g., poor calibration, starting recordings late) and/or missing data. For the second criterion, where participants needed to be looking within the central region of the stimulus for longer than 11% of the trial, an additional four participants were removed owing to not meeting this threshold. One additional participant was removed for having a saccade rate two to three times higher in some states (based on the analysis presented in the next paragraph) than other participants.

To analyze the eye movement data, we focused on comparing saccade rates under the different conditions. The method we used to define saccades was based on a commonly used model developed by Engbert and Kleigl (2003) (see also Schweitzer & Rolfs, 2020; van Dam & van Ee, 2006). To define saccades, we defined velocity thresholds for horizontal and vertical directions which were determined by scaling a robust estimator of the standard deviation by four for each trial. Based on our eye tracker's low frame rate (60 Hz), we lowered the scaling factor from six to four from the original model so that the saccade rates fall within a biologically plausible range for a task with a heavy cognitive load (e.g. Siegenthaler et al., 2014). The standard deviation included the entire trial length and then the trial's first and last five frames were trimmed before saccades were counted. We used the median of medians as our robust estimator (Schweitzer & Rolfs, 2020). Saccades were determined by frames of eye tracker data with either horizontal or vertical velocity that surpassed the threshold. The minimum length of a saccade detection was one frame of eye tracking data (approximately 16.7 ms), and adjacent frames above threshold were considered part of the same saccade. The direction of the saccade was determined by the angle between the position vector of two frames before the first frame and two frames after the last frame of the saccade. The frame buffer was added to decrease noise, and it was chosen at two frames to match the velocity sliding window of five frames. Saccades with angles between 45° and –45° or between 135° and 225° were categorized as horizontal and saccades outside that range were categorized as vertical. For the saccade analysis, we focused on six states of interest: two perceptual states (perceiving vertical, perceiving horizontal) times three instruction types (change, hold vertical, hold horizontal). The average rate of saccades per second was determined for each state for each participant. Because our eye tracker's frame rate is only 60 Hz, we caution interpreting the saccade rates as absolute measures and instead focus on their relative values across conditions.

The first set of questions we examined were 1) whether there are more or fewer saccades when participants were instructed to change compared with hold motion patterns and 2) whether, within the hold instructions, there were more or fewer saccades when participants were in a perceptual state consistent with the instruction (e.g., perceiving vertical motion when instructed to hold vertical) compared with inconsistent with the instruction (e.g., perceiving horizontal motion when instructed to hold vertical). To create a measure of the total saccade rate, we first summed the vertical and horizontal saccade rates for each participant. A 2×3 within-subjects ANOVA comparing perceptual state (vertical rebounding and horizontal rebounding) with instruction type (change, hold vertical, hold horizontal) revealed no main effect of perceptual state, $F(1,34) = .249$, $P = .621$, and no main effect instruction type, $F(2,68) = .019$, $P = .981$, on the total saccade rate. Additionally, there was no interaction between perceptual state and instruction type on the total saccade rate, $F(2,68) = 0.408$, $P = .667$ (Figure 5A).

The second set of questions we examined were 1) whether there is a bias for participants to make directional (vertical or horizontal) saccades, either when they are instructed to see vertical or horizontal motion or when they are perceiving vertical or horizontal motion, and 2) whether there was a bias for participants to make more directional saccades when they perceived motion consistent (e.g., perceiving vertical when instructed to hold vertical) or inconsistent (e.g., perceiving horizontal when instructed to hold vertical) with the instructions. We defined a measure of vertical saccade rate bias by taking the difference between the vertical and horizontal saccade rates for each participant. A 2×3 within-subjects ANOVA with factors of perceptual state (vertical rebounding and horizontal rebounding) and instruction type (change, hold vertical, hold horizontal) similarly revealed no

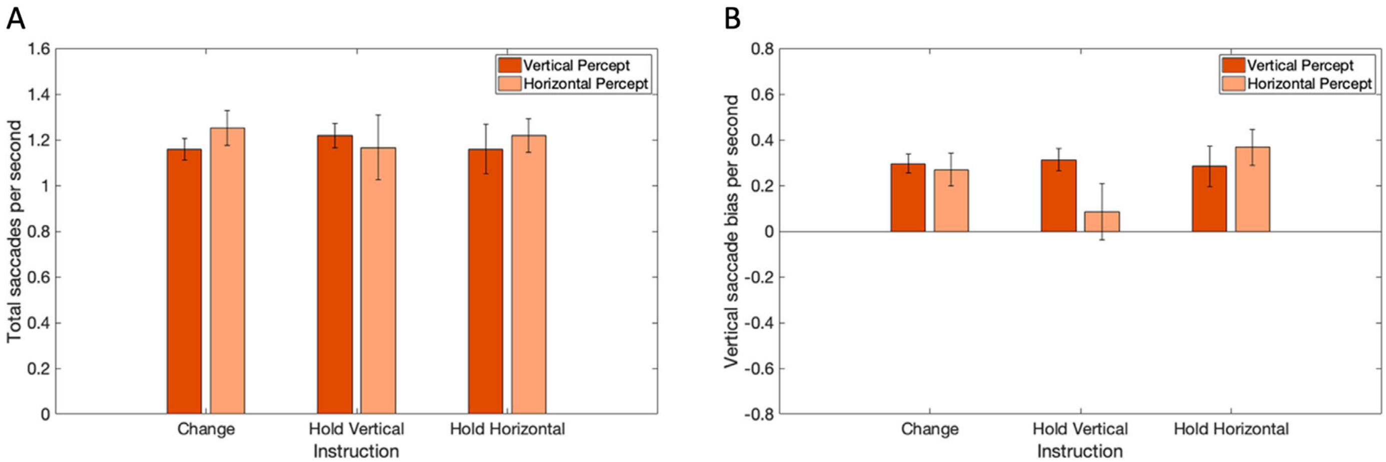

Figure 5. Saccades per second across the different perceptual states and instruction types for experiment 2. (A) The total saccades per second for periods where participants reported perceiving vertical and horizontal motion for each of the instruction conditions. (B) The vertical saccade bias per second, which can also be interpreted as the strength of participants' bias to saccade vertically, for periods where participants reported perceiving vertical and horizontal motion for each of the instruction conditions.

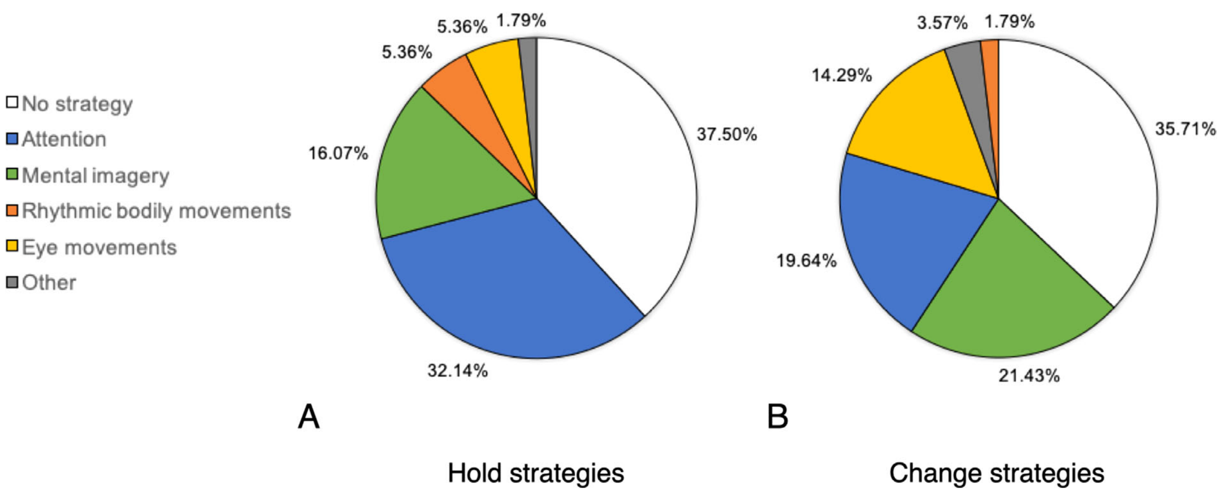

Figure 6. Survey results for experiment 2. (A) The distribution of strategies that participants reported using when they were instructed to hold. (B) The distribution of strategies that participants reported using when they were instructed to change.

main effect of perceptual state, $F(1,34) = 1.12$, $P = .297$, and no main effect instruction type, $F(2,68) = 1.66$, $P = .199$. Additionally, there was no interaction between perceptual state and instruction type, $F(2,68) = 2.58$, $P = .083$ (Figure 5B). Although there was an overall vertical saccade rate bias across conditions, the eye tracking analyses revealed no systematic relationship between saccade rates, percepts, or instructions.

Strategies reported

For the following analyses, only participants with coded responses for both questions 2 and 3 of the survey were included. Participants with at least one response that could not be categorized were removed. This resulted in the removal of four participants from the following analysis.

For hold trials, 37.50% of participants ($n = 21$) reported that they did not use a strategy, 32.14% ($n = 18$) reported using attention, 16.07% ($n = 9$) used mental imagery, 5.36% ($n = 3$) used eye movements, 5.36% ($n = 3$) used rhythmic bodily movements, and 1.79% ($n = 1$) used some other strategy (Figure 6A). For the change trials, 35.71% of participants ($n = 20$) reported that they did not use a strategy, 21.43% ($n = 12$) used mental imagery, 19.64% ($n = 11$) reported that they used attention, 14.29% ($n = 8$) used eye movements, 3.57% ($n = 2$) used a noncategorizable (other) strategy, and 1.79% ($n = 1$) reported using rhythmic bodily movements (Figure 6B).

For the participants who reported using eye movements in the survey, we first examined whether their subjective experience of using eye movements translated into differences in their overall saccades compared with participants who did not report using such a strategy. In particular, the strategies survey indicated that only three participants in the hold condition reported using eye movements as a strategy, compared with eight participants in the change condition. Unfortunately, two of the three participants who reported using eye movements in the hold condition had data that was removed from the eye movement analysis (for reasons mentioned in the Eye movement results section). For this reason, we examined whether participants' subjective experience of using eye movements translated into differences in their overall saccade rates compared with participants who did not report using eye movements as a strategy only within the change condition. Of the eight participants who reported using eye movements as a strategy for the change condition, one was removed from the eye movement analyses, leaving us with seven for the subsequent analyses. A two-sample t test comparing the overall saccade rates for participants who reported using eye movements as a strategy (mean, 3.50 per second; SE, 0.24) with participants who did not report using eye movements as a strategy (mean, 3.77 per second; SE, 0.13) within the change instruction condition found no difference between the two groups, $t(33) = 0.90$, $P = .373$.

Then, we examined whether participants' subjective experience of using eye movements as a strategy for the change condition translated into them having different overall saccade rates for change compared with hold instructions. The seven participants included in the subsequent analysis reported using eye movements as a strategy only for the change condition and not for the hold condition. A one-sample t test revealed no difference in participants' overall saccade rates for change (mean, 3.50 per second; SE, 0.24) compared with hold (mean, 3.97 per second; SE, 0.31) instructions, $t(6) = 2.08$, $P = .082$.

Discussion

Our behavioral results revealed longer button press durations for percepts consistent with the hold instruction (e.g., vertical percepts when instructed to hold vertical) compared with change durations, indicating that participants can control their perception of IAM. Participants are able to do so, even in a context where 1) initial percepts (of horizontal or vertical motion) have to be constrained from a large set of possible interpretations, rather than with the aid of motion priming, and 2) percept reporting is more challenging because participants are reporting their percepts dynamically throughout the trial (as opposed to a single report per trial). As mentioned elsewhere in this article, despite the plethora of research showing that subjective control is possible across a variety of ambiguous or bistable stimuli, it was not a priori obvious that participants should be able to control their percepts in IAM owing to some of IAM's properties that make it different from other polystable stimuli. For instance, it is possible that forming coherent percepts in IAM may be more demanding, because participants have to first constrain from a large set of possible interpretations to perceive the particular motion (e.g., vertical or horizontal rebounding) to subsequently take the steps to control it, whereas other stimuli offer at least one interpretation automatically. This possibility highlights the importance of the results obtained here showing that participants can subjectively control the motion even when the assistance of motion priming for forming the initial percept is removed from the task. Furthermore, should participants lose their intended percept during the task, they seem to be able to continue reconstraining the motion pattern percept out of pure noise. Additionally, in this task, where no motion priming is present, participants then have to control their percept in light of many (practically unbounded) possible alternatives. Again, the results from this experiment highlight that naive observers can control IAM beyond a simple one-time change as instructed of them in experiment 1, but can continue to control their percepts across a 10-second trial in light of these potentially competing perceptions. Each of these steps represents a potential difficulty for participants that could have resulted in them being unable to control IAM.

The role of eye movements

Previous research examining the subjective control of polystable stimuli finds that eye movements, although they can at times facilitate, are not essential for subjective control (Brouwer & van Ee, 2006; Kohler, Haddad, Singer, & Muckli, 2008; Liu et al., 2012; Toppino, 2003; van Dam & van Ee, 2006; van Ee, van Dam, & Brouwer, 2005). Similarly, Davidenko and colleagues (2018), with the use of annulus displays of rotating IAM, argued that eye movements were not essential for perceiving IAM. We conducted two analyses examining the role of saccades. The first analysis examining whether participants had more saccades when they were instructed to change compared with hold found no difference in total saccade rates between instructions. The first analysis also examined whether, during instructions to hold, participants made more eye movements during perceptual states consistent with or inconsistent with the hold instruction and also found no difference in total saccade rates. Taken together, these findings suggest that there was no connection between participants' total saccade rates and their perceptual experience of certain motion directions (vertical or horizontal) or their intentions to see a certain type of motion.

The second analysis examining whether there is a bias for participants to make directional (vertical or horizontal) saccades when they are either instructed to or are perceiving a particular direction found no directional bias. Additionally, the second analysis examines whether there was a bias for participants to make more directional saccades when they perceived motion consistent or inconsistent and found only an overall bias for vertical saccades. Similar to the first analysis, this finding suggests that there was no bias for participants to make saccades particular to the different perceptual states or during different control instructions. Taken together these findings suggest that saccades were not essential in participants controlling their percepts while viewing IAM.

Participant strategies for subjective control

Previous research considers strategies that participants might employ while performing the task. For example, Kornmeir, Hein, and Bach (2009) and van Ee and colleagues (2005) suggest that, when participants are holding a particular percept, they could be doing so by increasing the stability of the instructed percept, by decreasing the stability of the noninstructed percept, or doing a combination of both. From there, researchers may use stability durations to infer which of these strategies participants used. Van Ee and colleagues (2005) suggest that, based on the pattern of durations that they found, when participants are holding percepts it is likely happening through the strategy of making the instructed percept more stable. They also suggest that the strategy may have differed by instruction. In addition, much of the research on subjective control of polystable stimuli suggests that attention or selective attention is likely an important factor for subjective control (e.g., Leopold & Logothetis, 1999; Pitts, Gavin, & Nerger, 2008; Slotnick & Yantis, 2005; Windmann et al., 2006). What is left out of such considerations and mechanisms is this: What do participants think they are doing when they subjectively control the motion?

Our survey findings, although exploratory and inconclusive, provide, to our knowledge, some of the first evidence of what participants think they are doing when attempting to subjectively control their percepts. In particular, for both types of instructions, we found a range of strategies, including the use of eye movements, mental imagery, and attention. We also found a substantial number of participants who reported employing no strategy for controlling the motion. Additionally, we explored whether 1) participants who reported using eye movements as a strategy in the change condition showed any differences in their overall saccade rates compared with participants who did not report using eye movements as a strategy and 2) there was any difference in their overall saccade rate when instructed to change compared with hold. For the first analysis, the results revealed no difference in the overall saccade rates between the two groups, suggesting that participants who reported using eye movements to control the motion did not produce different overall saccade behaviors from those who did not. For the second analysis, the results found no difference in participants' saccade rates for the different conditions, suggesting that participants' subjective strategy to use eye movements when instructed to change did not produce different saccade behaviors compared with when they were instructed to hold the motion. Taken together, these findings suggest that participants' subjective experience of using eye movements to control their perception of IAM did not translate into saccade behavior that differed from participants who did not report using eye movements as a strategy or that differed between instruction conditions.

General discussion

The main purpose of our studies was to test whether it is possible for naive observers to control their perceptions of IAM, akin to how they can control their percepts in other simpler ambiguous stimuli. Experiments 1 and 2 collectively extend previous research on the relationship between subjective control and polystable stimuli, suggesting that, despite IAM being a novel kind of polystable stimulus with a multitude of possible interpretations, it is still possible for naïve participants to exert control over their percepts over a variety of contexts. They also collectively demonstrate that some of our a priori concerns (i.e., participants having to constrain the initial motion percepts from an unbounded set of possible interpretations, maintaining percepts in the face of competition from many other possible interpretations) that IAM might not be controllable like other polystable were not founded. Nevertheless, these peculiar properties of IAM are worthy of future exploration in the context of subjective control.

Although experiments 1 and 2 use different paradigms and measures that are difficult to compare, we observed in both studies a pattern of results that suggest that participants are able to control their perception of motion in IAM through a combination of increasing the duration of the desired and shortening the duration of the undesired percepts. Experiment 1 suggests that participants were able to suppress an undesired percept to change the motion and to increase the duration of a desired percept to hold the motion, and the effect of control was greater in the change condition suggesting that participants may have been

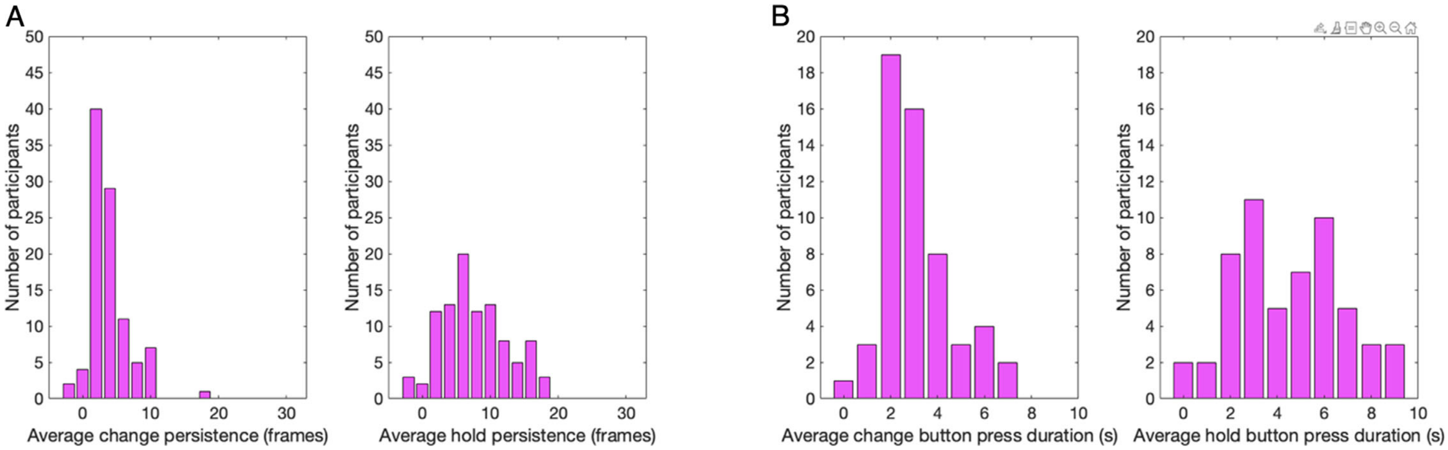

Figure 7. Individual differences in experiments 1 and 2. (A) The distribution of mean persistence across trials in experiment 1. The left histogram shows the distribution of persistence for change instructions, and the right histogram shows the distribution of persistence for hold instructions. (B) The mean button press duration across participants in experiment 2. The left histogram shows button press durations during change trials (collapsed across perceptual state), and the right histogram shows button press durations during hold trials (collapsed across perceptual states consistent with the instruction).

more effective at suppressing than increasing motion percepts. Meanwhile, experiment 2 suggests that participants were able to control their percepts during hold instructions by increasing the desired percept while also suppressing undesired percepts, and the greater mean difference between hold consistent and change trials suggests that the influence of increasing the desired percept is greater. Collectively, the results from experiments 1 and 2 suggest that participants may control their perception of IAM motion through a combination of increasing and decreasing percept durations.

Individual differences and future directions

Previous research on IAM in work by Davidenko and colleagues (2017) demonstrates that there are substantial individual differences between participants when viewing IAM. The amount of motion persistence individual participants experienced following one type of motion prime (e.g., rebounding) also tended to correlate with the amount of persistence following other motion primes (e.g., drifting), suggesting that there are individual differences in how long participants see IAM. This finding was replicated across two of their experiments using different sets of participants.

We also found substantial individual variability in the degree to which participants are able to change and hold their percepts while viewing IAM (Figures 7A and 7B). Given the substantial sample sizes collected from experiments 1 and 2, we expect this pattern of results to be obtainable in future studies.

The individual differences found in experiments 1 and 2 leave open questions worthy of future exploration. One significant question is whether the individual differences we observed occur owing to 1) differences in participants' ability to perceive coherent motion in IAM (such as in Davidenko et al. [2017]), 2) in participants' ability to control their percepts, 3) the decision criteria for reporting particular percepts as present, or 4) some combination of the three. Although we have assumed here that IAM is a polystable stimulus, as mentioned elsewhere in this article, some of its properties make it unclear whether it is appropriate to place in this category. For example, our question about whether individual differences arise owing to 1) participants' ability to perceive coherent motion and 3) the decision criteria for reporting particular percepts in IAM are somewhat unique to IAM owing to its high noise and high amount of visual transients compared with simpler polystable motion stimuli (such as apparent motion quartets).

This finding connects to a related question of how subjective control of IAM relates to subjective control in other kinds of polystable stimuli. Previous research comparing control across polystable stimuli has already demonstrated that the degree to which participants can exert subjective control can vary by stimulus (Meng & Tong, 2004; Pastukhov, Kastrup, Abs, & Carbon, 2019; van Ee, van Dam, & Brouwer, 2005; Windmann et al., 2006). Even now that experiments 1 and 2 have shown participants can control IAM subjectively, it is unclear whether IAM may be more or less challenging to control than other polystable stimuli or whether IAM may share properties (or correlate) with other stimuli under subjective control conditions. For example, IAM and apparent motion quartets share the property of polystability. However, unlike apparent motion quartets, for participants to perceive the instructed motion, the motion pattern must first be constrained from a large set of possibilities available in the pure noise motion signal, and then participants have to control that motion pattern. This process can potentially occur over and over again throughout the trial if participants lose the instructed motion pattern. Additionally, because the motion pattern is being constrained from pure noise, the motion signal that participants perceive may have differing levels of coherence or clarity. This process may result in individual differences in thresholds for deciding whether or not to categorize certain perceptions for perceptual reports. For apparent motion quartets, subjective control may be more straightforward because quartets are typically resolved in only up to four interpretations (vertical, horizontal, clockwise, or counterclockwise), and the viewer experiences at least one of the interpretations without conscious effort, then they can subjectively control what is perceived among those few competing interpretations.

As a preliminary comparison with apparent motion quartets, we compared our mean duration of button presses with phase durations reported in Kohler et al. (2008). We found that the mean duration of button presses was 3.15 seconds for change (when collapsed across perceptual state) and 4.48 seconds for hold (collapsed across perceptual states consistent with the instruction). The mean absolute phase duration for apparent motion quartets was 7.2 seconds for change and 32.5 seconds for hold (for larger quartets). From this comparison, the durations are much shorter for IAM compared with apparent motion quartets. However, our trials were much shorter (only 10 seconds compared with 2-minute trials in Kohler et al. [2008]), which may have biased our durations. Future research could explore to what extent IAM shares properties with other polystable stimuli, using both behavioral and neurological measures. This process could help to elucidate whether IAM should be considered in the same category as other polystable stimuli and whether it is easier or more difficult to control compared with other stimuli.

Finally, a limitation of our study, and one that arises with tasks similar to ours, is a problem with determining whether the results obtained are due to the nature of participants' perceptions changing or due to their response behavior changing. For example, it could be that, rather than participants controlling their percepts in IAM, their decision threshold for reporting particular motion patterns is what is being influenced by the task. As mentioned elsewhere in this article, perceiving a motion pattern in IAM may be based on different levels of coherence across participants, reflecting individual differences in decision criteria for reporting whether a particular motion pattern is being perceived. It is possible that, in our study, some combination of participants' perceptions and decision criteria are being modified by our instructions. The robust rebounding bias observed in experiment 1 suggests that what we are seeing is not simply experimental demand. However, future research is needed to tease apart the role of decision making in the perceptual reports for IAM.

Conclusions

The experiments presented here sought to answer the question of whether subjective control of polystable stimuli extends to IAM, a new, maximally ambiguous motion stimulus. Experiment 1 demonstrated that participants are able to control their perception of IAM in a context that involves motion priming (assisting with the perception of the initial motion pattern) and where participants reported only one perceptual change, if it occurred, during the trial. This experiment, based on previous IAM paradigms, demonstrated that control of IAM is possible. Experiment 2 sought to bring the methods more in line with other studies examining subjective control of polystable stimuli by removing the motion priming, and instead requiring participants to constrain from a large set of possible motion patterns. Additionally, participants reported their percepts dynamically across the 10-second trials. Even with this potentially more challenging task, participants were able to demonstrate substantial subjective control over their percepts of IAM.

Keywords: voluntary attention, apparent motion, polystable stimuli, illusory apparent motion

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Supplementary materials

Supplementary Video 1. An example change trial from experiment 1 depicting drifting motion in the first five frames and random changes thereafter.

Supplementary Video 2. An example hold trial from experiment 1 depicting rebounding motion in the first seven frames and random changes thereafter.

Supplementary Video 3. An example change trial from experiment 2.