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THE NATURE OF SUBJECTIVE CONTROL OF ILLUSORY APPARENT MOTION

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Abstract

The nature of subjective control of Illusory Apparent Motion

Allison K. Allen

Polystable phenomena have been extensively studied to understand the constructive nature of perception (e.g., the Necker cube, duck-rabbit, binocular rivalry). A new polystable phenomenon, illusory apparent motion (IAM), with unique properties was recently discovered (Davidenko et al., 2017). IAM is generated in randomly refreshing pixel arrays. As a result, IAM, unlike other polystable phenomena, affords potentially counterless interpretations of the pixel motion and observers may not automatically experience an initial interpretation, instead having to rely on self-generated initial percepts. These unique properties of IAM raise a plethora of questions.

In light of IAM's unique properties, the four experiments presented here explore questions about the nature of subjective control of IAM. Experiments 1 and 2 ask whether observers can mentally control their perception of IAM (a feature common in other polystable phenomena). Experiment 1 explores this question using a motion priming and persistence task, based on the methods of Davidenko et al. (2017). Participants were presented with a series of priming frames that transitioned to frames of pure noise and reported with a single button press when the initial motion pattern appeared to change. Experiment 1 found that observers were able to mentally control IAM, evidenced by extended motion persistence when they were

instructed to 'hold' and shortened motion persistence when they were instructed to 'change.' Experiment 2 explores the same question, but in a methodological context more in line with past subjective controls studies (Kohlers et al., 2008). For this task, participants were not assisted with motion primes, instead self-generating initial motion patterns, and reported their percepts dynamically throughout the trial. Experiment 2 found that participants were able to control their perception of IAM in this new, possibly more demanding, experimental context. Together, the results of Experiments 1 and 2 demonstrate that participants can subjectively control their perceptions of IAM.

Experiment 3 explored questions about the potentially countless interpretations of IAM: how many interpretations of IAM can observers perceive and subjectively control? Experiment 3 tested 14 different motion types, half of which were motion types not yet explored in IAM studies (i.e., containing expansion, contraction, and shearing motion patterns). For each trial, participants were informed about one of the 14 motion types of instruction and, for one block, reported when they happened to perceive the instructed motion. In another block, participants were instructed to try and 'hold' the instructed motion. Experiment 3 found that observers were able to perceive many and control a few interpretations of IAM, supporting previous assumptions that observers likely experience more interpretations of IAM than other polystable phenomena.

The last study, Experiment 4, explored whether it was possible to quantify some of the low- and high-level factors that can influence participants' perception of

IAM (e.g., subjective control, motion biases, motion coherence). To test this, participants were presented with two priming frames, followed by two test frames. The test frames were manipulated to present participants with (1) a nulling (prime-inconsistent) motion below and above their perceptual threshold, (2) with a facilitating (prime-consistent) motion below and above their perceptual threshold, and (3) with 0% motion. After each trial, participants reported the direction of motion that they perceived on the final two frames. Experiment 4 demonstrates that it's possible to quantify a number of factors, including: the strength of the rebound bias, subjective control, motion nulling, and motion facilitation.

Taken together, Experiments 1-4 lay the initial groundwork for exploring subjective control of IAM. Together they demonstrate subjective control in a variety of task conditions, suggest which motion types participants can control, and quantify the strength of subjective control.

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Chapter I

General introduction

Polystable phenomena have long been of interest to perception researchers. Polystable phenomena are a class of illusions characterized by observers' experience of the stimulus switching back and forth between different interpretations or organizations. For example, the Necker cube may be perceived as either having a front-facing or a top-facing orientation (Figure 1A). In another example, the face-vase may be perceived either as a vase or the profiles of two faces (Figure 1C). Notably, in each of these examples, as is characteristic of polystable phenomena, the retinal image is the same. Polystable phenomena such as these are of interest to perception researchers as the phenomena allow us to explore the constructive nature of perception.

One of the main features of polystable stimuli is that observers tend to experience different interpretations of the stimulus over time (Leopold & Logothetis, 1999). Typically studies present observers with polystable stimulus displays for durations around 30 seconds to a couple of minutes. During these display periods, participants report periodically experiencing reversals every few seconds (e.g., Pöppel, 1997). According to a model by Long and Toppino (2004), the dynamics of such reversals may occur due to competition between different interpretations, and that such competition is resolved at a representational, or intermediate, stage of processing.

Consistent with this account, past research suggests that competing representations can be biased by lower and higher level factors. For instance, research suggests that stimulus features such as geometry (e.g., Radilova et al., 2008), eccentricity (e.g., Suzuki & Peterson, 2000), density (e.g., Brouwer & van Ee, 2006), and timing (e.g., Leopold, Wilke, Maier, & Logothetis, 2002) can bias stimulus reversals. Similarly, higher-level factors such as subjective control (e.g., Kohler, Haddad, Singer, & Muckli, 2008; Liu, Tzeng, Hung, Tseng, & Juan, 2012; van Ee, van Dam, & Brouwer, 2005), learning (e.g., Harrison & Backus, 2010; Long, Toppino, & Kostenbauder, 1983), knowledge (e.g., Rock, Hall, & Davis, 1994), performed action (Wohlschläger, 2000), and attention (e.g., Chong & Blake, 2006; Paffen, Alais, & Verstraten, 2006) have been demonstrated to bias polystable perception. Importantly, even with these different factors biasing polystable perception, in many contexts observers still experience the *automatic* switching of the perceptual representation.

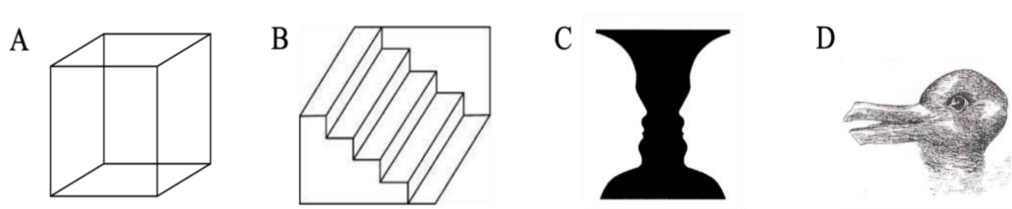

Figure 1. A.) The Necker cube, B.) Schröder's staircase, C.) Face-vase, D.) Duck-rabbit. Each one of these polystable stimuli has two possible interpretations. Sources: Necker cube (Louis Albert Necker), Schröder's staircase (Heinrich G. F. Schröder), Face-Vase (Edgar Rubin), duck-rabbit (Fliegende Blätter).

Polystable phenomena have a couple of additional characteristics worth noting. One is that most polystable phenomena often have two interpretations that observers will switch back and forth between (Figure 1A-D). As a result, conceptualizations of polystable perception often deal with perception having to resolve between two competing interpretations of the stimulus. Another characteristic worth noting is that, in most cases of polystable perception, observers will automatically experience one of the interpretations. Going back to the example of the Necker cube, most observers automatically experience the object as organized into either the front-facing or top-facing interpretation (Figure 1A). Similarly, for the duck-rabbit, most observers automatically experience the image as either a duck or a rabbit (Figure 1D).

Recently, a new polystable stimulus called *illusory apparent motion* (IAM)[1] was discovered (Davidenko, Heller, Cheong & Smith, 2017). IAM is a polystable stimulus in which ambiguous apparent motion is generated by presenting observers with randomly refreshing pixel arrays across a series of frames at a relatively slow pace (1-3 Hz). One feature that distinguishes IAM from other polystable stimuli is that it offers a much larger space of possible interpretations of the stimulus. For example, observers may experience more than two motion patterns (e.g., up-down, up-up, shear motion, contraction-expansion, etc.) and directions (e.g., up, down, left, right, diagonal, rotating, etc.). This large space of possible motion interpretations stands in contrast to the relatively smaller space of possible interpretations in other

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[1] An animated gif of Illusory Apparent Motion can be viewed here: https://bit.ly/3zHFQ3G

polystable stimuli. Another feature that distinguishes IAM from other polystable stimuli is that observers may not *automatically* experience a coherent organized interpretation. Anecdotally, many observers report simply seeing “random” until primed or suggested otherwise.

The unique properties of IAM raise new questions about how the stimulus may or may not differ from classic polystable phenomena. The experiments presented here focus on IAM within the context of subjective control. Subjective control occurs when observers bias how polystable phenomena appear by mentally controlling (using intention or voluntary control) which interpretation of the stimulus is dominant. Subjective control has been demonstrated in a wide variety of polystable phenomena, including for instance, binocular rivalry (Meredith & Meredith, 1962; Paffen & Alais, 2011), the Necker cube (e.g., Long, 2003; Peloton & Solley, 1968), structure-from-motion cylinder (e.g., Brouwer & Van Ee, 2006), apparent motion quartets (e.g., Kohler, Haddad, Singer, & Muckli, 2008), the silhouette spinner (Liu, Tzeng, Hung, Tseng, & Juan, 2012), and numerous others. However, the unique properties of IAM raise questions about observers’ ability to control the stimulus. In particular, the many possible interpretations of IAM and the chance that observers may have to self-generate initial interpretations of the stimulus could make subjective control more difficult.

Chapter II presents two studies (Experiments 1 and 2) that were the first to explore whether observers can subjectively control their perception of IAM. Experiments 1 and 2 explore this question using two different presentation configurations of IAM. First, Experiment 1 uses a design similar to Davidenko et al. (2017) and presents participants with a series of rebounding or drifting priming frames, followed by a series of random frames. Participants control the motion by either trying to change what they see from the initial motion pattern or trying to hold the initial motion pattern. On each trial they report using a single button press to indicate when the motion appears to change from the initial motion pattern. For this study, participants didn't have to do the work of initially generating a motion pattern. Instead, participants were primed with an initial motion pattern.

Experiment 2 builds on Experiment 1 by using a subjective control design more similar to designs used for other polystable stimuli (e.g., Kohler et al., 2008). Experiment 2 explores this question in an experimental context that presents IAM without priming frames and while participants dynamically reported their perceptions during trials. It's possible that a task such as this may be more challenging for participants because the perception of motion first needs to be generated from pure noise, then the motion has to be controlled over time. In this experiment, participants are instructed to change back and forth from a vertical rebounding to a horizontal rebounding motion pattern, hold a vertical rebounding motion pattern, or hold a horizontal rebounding motion pattern. During each trial participants reported when they experienced a vertical or horizontal rebounding motion (or "other"). Observers' eye movements were monitored during the task, and vertical and horizontal saccade rates were analyzed. At the end of the experiment, participants completed a survey about what strategies they used while trying to control the motion.

Chapter III presents Experiment 3, which explores IAM's property of being maximally ambiguous. The study tests participants' ability to perceive and subjectively control 14 different types of motion. The 14 motion types that we tested include previously tested motion patterns (translation and rotation), as well as previously untested motion types (expansion, contraction, and shear). To test whether participants could perceive a given motion type, they were instructed to report (by holding down a key) whenever they happened to experience a specified (e.g., translational vertical rebounding) motion type. Then, to test whether participants could subjectively control the 14 motion types, they were instructed to 'try to hold' a specified motion type. After each trial (when testing perception and subjective control), participants were prompted to rate (on a 1-8 Likert scale) how clear/vivid the motion appeared. After each subjective control trial, participants were prompted to rate (on a 1-8 Likert scale) how difficult it was to see the motion.

Chapter IV presents Experiment 4, which explores whether different high- and low-level factors can be quantified using a motion nulling procedure. Experiment 4 determines each participant's threshold for detecting the presence of motion in IAM displays. Then each participant's threshold is used for critical trials to determine 'above threshold' (add 10% to the participant's threshold) and 'below threshold' (subtract 10% from the participant's threshold) manipulations. The main task presents participants with two priming frames and two test frames of IAM. The baseline test frames present participants with random motion (0% motion). The remaining test frames were manipulated to either nullify or amplify participants' perception of the primed motion pattern. Inconsistent trials presented a motion signal in the opposite direction of the priming motion at coherence above participants' threshold or below participants' threshold. Consistent trials presented motion that was consistent with the priming motion. Half of consistent trials included motion coherence above participants' threshold and the other half included motion coherence below participants' threshold. These conditions were first tested in a passive block where participants were instructed to observe the motion and report the motion in the final two test frames, and then in a subjective control block where participants were instructed to try to hold the motion prime into the test frames. The study aims to quantify the strength of motion nulling (through prime-inconsistent test frames), the strength of perceptual facilitation (through prime-consistent test frames), the rebound bias, and subjective control.

Chapter II

Subjective control of Illusory Apparent Motion

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, 1994; 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 paper, 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; 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 3 frames per second, it becomes challenging to change between vertical and horizontal percepts. A later study by Kohler and colleagues (2008) explored 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 (up to 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, etc.) and directions (e.g., up, down, left, right, diagonal, rotating, etc.). It is also possible to introduce non-ambiguous 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 non-rebounding 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/counter-clockwise, 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 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., Kohler et al., 2008; Hol, Koene, & van Ee, 2003; Pelton & Solley, 1968; 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 as IAM may have unique challenges associated with it. First, due 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, in order 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 presents a unique challenge for IAM because it may be difficult to re-constrain a motion pattern once it is lost. This 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. On the other hand, 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 (3, 5, or 7) of priming frames which 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 due 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.

Method

Participants

99 (M_{age} = 19.49, SD_{age} = 1.15; Female = 57, NB = 1) University of California, Santa Cruz (UCSC) undergraduates 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 x 560 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 x 140 pixel window sampled from within the background array that subtended approximately 9.45° x

9.45° of visual angle (Figure 2A). 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 in order 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.

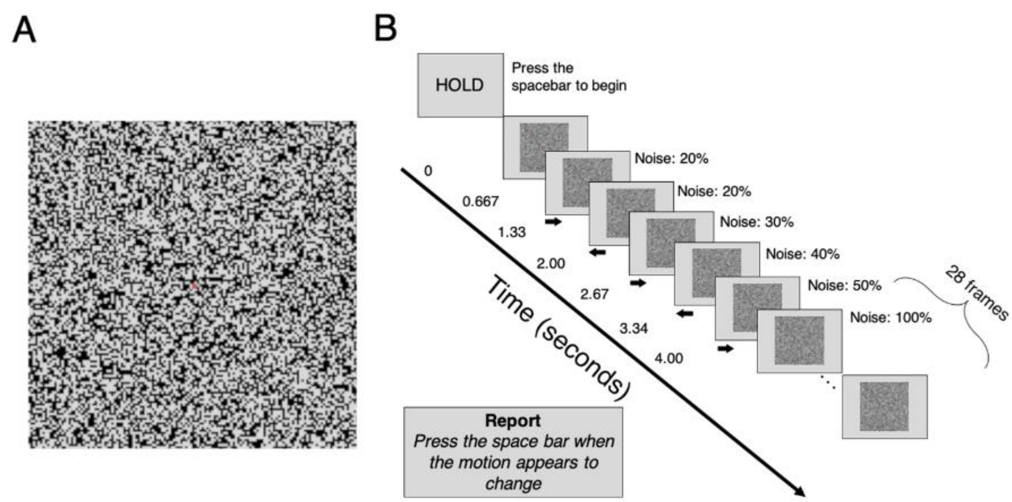

Figure 2. The stimulus and trial sequence used in Experiment 1. A.) A single stimulus frame with a red fixation dot. B.) An example trial sequence depicting the hold instruction and five frames priming a horizontal rebounding pattern. During the hold instruction, participants were instructed to try to hold the initial motion pattern for as long as possible. Across an approximately 22 s 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 appeared to change from the initial priming motion.

During each trial, participants were presented with either 3, 5, or 7 motion priming frames, followed by up to 29, 27, or 25 pure-noise frames, respectively, such that each trial presented up to 33 frames. This amounted to trials that were up to 22 s 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 3 priming frames, 80% of the pixels moved with coherent motion, and in trials with 5 and 7 priming frames, the frames following the first 3 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 in order 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 .667 s; see Figure 2B).

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 prior to 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.

Following 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’ since 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.

Prior to 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 s demo 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 appears 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 appeared 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 appeared 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 following 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 persistence under 250 ms assuming these 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 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 may be a good measure, 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 *no response trials* (NRTs; Figure 3A).

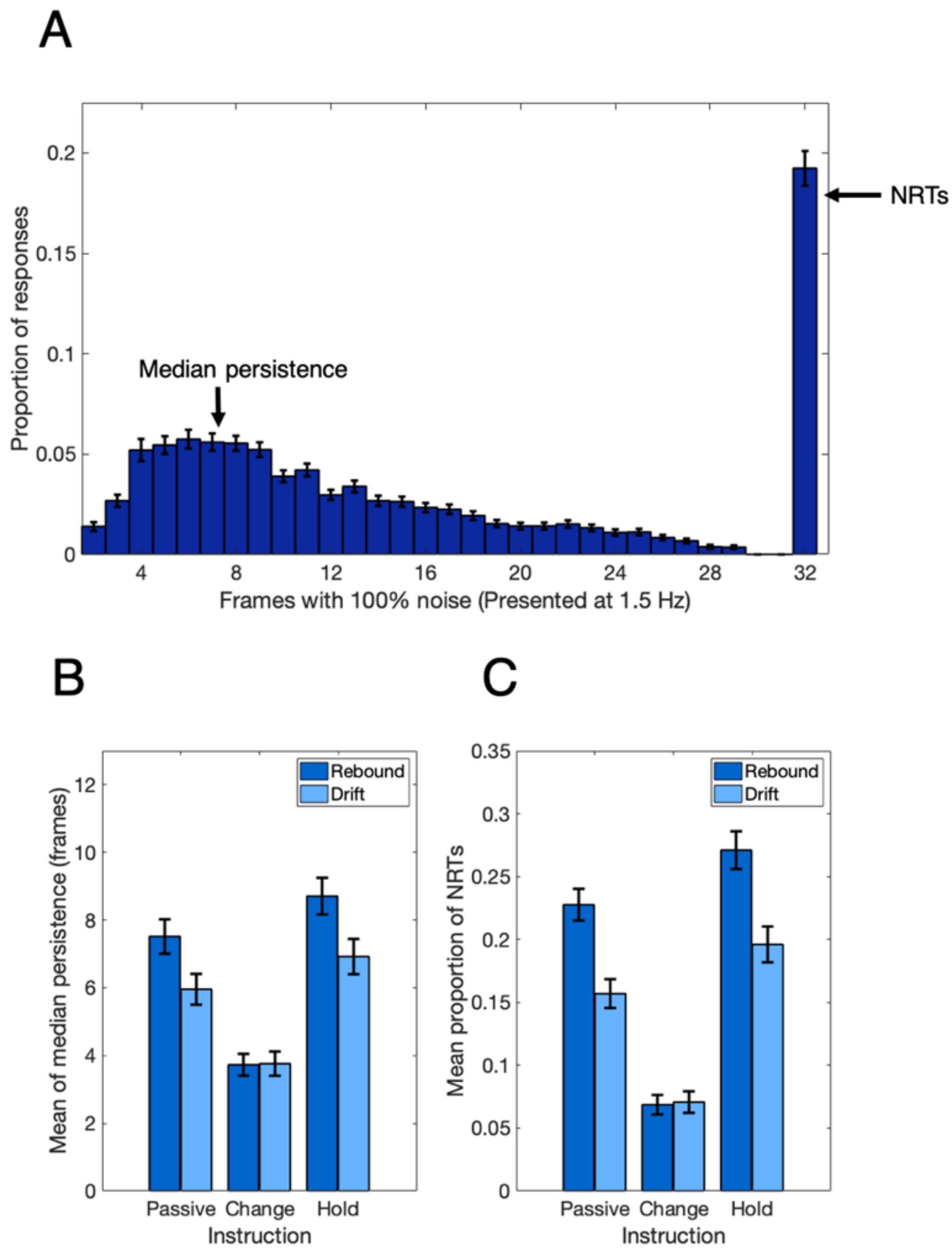

Figure 3. Results of Experiment 1: A.) Distribution of motion persistence during pure-noise frames, collapsed across motion patterns and priming conditions in the passive block of trials. Each bar represents the proportion of responses on each noise frame indicating when motion persistence of the initial priming frames ended. The

bar on the right (labeled 32 on the x-axis) indicates the proportion of no response trials (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 to hold and passive instructions. Moreover, hold instructions results in reports of longer motion persistence compared to 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 to 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 3-way ANOVAs. A 3 x 2 x 3 repeated measures ANOVA comparing durations of motion persistence by the number of priming frames (3, 5, 7), type of motion prime (rebound and drift), and instruction type (passive, change, hold; see Figure 3B) importantly revealed a main effect of instruction such that change instructions has the shortest mean persistence (M = 3.69 frames, SE = 0.16), following by passive (M = 6.74 frames, SE = 0.22), and hold persistence had the longest mean persistence (M = 7.66 frames, SE = 0.24), $F(2,196) = 54.15$, $p < .001$. There was also a main effect of motion type such that rebounding motion primes (M = 6.65 frames, SE = 0.19) resulted in reports of longer motion persistence compared to drift motion primes (M = 5.55 frames, SE = 0.17), $F(1,98) = 14.97$, $p < .001$. There was also a main effect of priming frames wherein the fewer priming frames presented, the longer the reported motion persistence (3 frames: $M = 6.94$ frames, $SE = 0.23$; 5 frames: $M = 5.94$ frames, $SE = 0.22$; 7 frames: $M = 5.36$ frames, $SE = 0.21$), $F(2,196) = 40.67$, $p < .001$. Among the possible interactions, there was a significant interaction between the type of priming frame and instruction, $F(2,196) = 9.61$, $p < .001$, reflecting that the effect of motion type (i.e. the rebound bias) was more pronounced during passive and hold instructions compared to change instructions during which there was no rebound bias.

A similar 3 x 2 x 3 repeated measures ANOVA comparing the mean proportion of NRTs by the number of priming frames (3, 5, 7), type of motion prime (rebound and drift), and instruction type (passive, change, hold; see Figure 3C) also, importantly, revealed a main effect of instruction such that change instructions had the lowest mean proportion of NRTs ($M = 0.07$, $SE = 0.01$), followed by passive ($M = 0.19$, $SE = 0.01$), and hold instructions had the largest mean proportion of NRTs ($M = 0.23$, $SE = 0.01$), $F(2,192) = 41.44$, $p < .001$. There was also a main effect of motion type such that rebounding motion primes ($M = 0.19$, $SE = 0.01$) resulted in a greater proportion of NRTs compared to drift motion primes ($M = 0.14$, $SE = 0.01$), $F(1,98) = 19.66$, $p < .001$. Among the possible interactions, there was only one significant interaction between the type of priming frame and instruction, $F(2,196) = 11.08$, $p < .001$, again revealing that the rebound bias was more pronounced during passive and hold instructions compared to 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 show no interactions in the above analyses, we chose to collapse across the number of priming frames for the subsequent analyses. We ran a series of 2 x 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 x 2 ANOVAs. The results from the persistence analyses revealed a consistent main effect of instruction (all pairwise p-values $< .005$) and the type of motion prime (all pairwise p-values $< .05$). Similarly, the results from the NRTs analyses revealed a consistent main effect of instruction (all pairwise p-values $< .05$) and the type of motion prime (all pairwise p-values $< .05$). Additionally, for both persistence and NRT measures, there was an interaction such that the rebound bias was greater during hold and passive instructions compared to change instructions (all pairwise p-values $< .001$; see Figures 3B & 3C).

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 to durations of motion persistence during passive instructions, participants were able to both (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 to increasing it in the hold relative to the passive condition (an increase of 13.7%). This 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 to 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's 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) in order to streamline the experiment and include catch trials. First, because Experiment 1 demonstrated a larger proportion NRTs for rebounding instructions suggesting that it was easier for participants to control rebounding compared to 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 below) to ensure participants were reporting their actual percepts rather than simply reporting the instructed motion.

Method

Participants

76 (M_{age} = 20.02, SD_{age} = 1.70; Female = 39) UCSC undergraduates 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 min 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 was collected with Matlab software (Kleiner, Brainard, & Pelli, 2007). Instructions were presented in 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 s (Figure 4B). Finally, to check for experimental demand, we included 6 additional trials that contained non-ambiguous 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. 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.

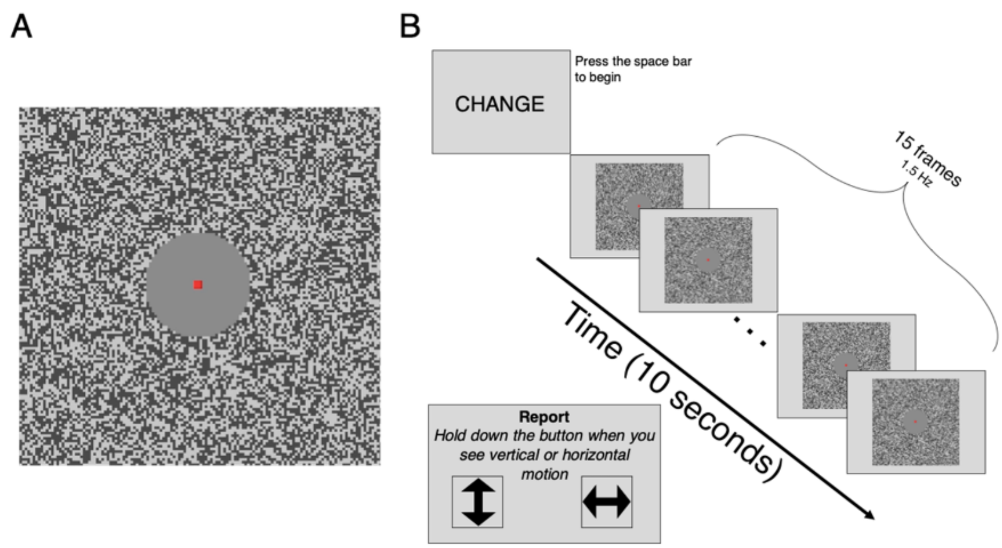

Figure 4. The stimulus and trial sequence used in Experiment 2: A.) A single stimulus frame with a fovea mask and red fixation dot. B.) An example trial sequence depicting the change instruction. During the change instruction participants were instructed to change from a horizontal rebounding to vertical rebounding pattern as quickly as possible. Across a 10 s 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.

Procedure

Participants began the study by being informed about 'vertical' and 'horizontal' motion. For the purpose 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 s) demonstration of each motion type with 100% motion signal was presented to participants to clarify the descriptions of the motion 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).

Following the practice trials, subjects were informed that the stimuli they would be shown during the study can sometimes be mentally controlled. Participants were also informed that a prompt instructing them to either (1) “*change between vertical and horizontal motion patterns as quickly as possibl*e,” (2) “to *hold a vertical motion pattern for as long as possibl*e,” 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 8 times and were presented in random order. This, combined with the 6 catch trials (detailed in the next section), resulted in 30 total trials in the experiment. Participants self-initiated each trial by pressing the spacebar. Importantly, in order to control for the possible influence of eye movements, participants were instructed to maintain fixations within the grey fixation region. Participant eye movement data was collected (see eye tracking section below).

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 above). 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 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 1.0-1.5 degree of accuracy. First, for analyses that were conducted in order 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 s of each trial. The middle 8 s of each trial was analyzed in order 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 5 frames of each trial (amounting to 83 ms removed from the beginning and end of each trial), leaving the middle 9.83 s of each trial. The middle 9.83 s of each trial was analyzed, again, in order 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 6 or 8 questions, depending on whether subjects indicated that they did (8 questions) or did not (6 questions) use strategies. The survey included yes/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 paper, 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 A for all survey questions.)

Behavioral data analysis

Participants reported their percepts by pressing one of two buttons throughout a 10 s trial. The main measure we used, *mean button press duration,* was obtained by collecting individual percept durations within a trial, then taking an average duration for each trial. This 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, “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 s 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 s 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 section, 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’s not clear to what extent this would also be true of IAM. Question 5 of the post-experiment 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 A). As mentioned above, 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 non-visual imagery), (5) attention, and (6) other (i.e., anything not captured by the first 5 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 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, motor, etc.). For example, participants who reported thinking the words “up-down-up-down” in their mind would have been 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 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 MJ) 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* (Hayes & Krippendorf, 2007; Krippendorf, 2008, 2011). Krippendorf’s 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 around 0 indicates no relationship (or random) agreement among raters. Krippendorf’s alpha ($K\alpha$) was calculated using a freely available Matlab function (Eggink, 2021). The reliability of coders agreement for questions 2 and 3 was $K\alpha = 0.68$, which is above the acceptable minimum for Krippendorf’s alpha (De Stewart, 2012).

To see how the reliability of our coders compared to the range of possible random responses we ran a simulation based on randomizing the responses of each of our coders in order to capture what it would look like if that particular person were simply coding randomly. Once each individual's ratings were randomized, they were re-combined with the scores of the other three coders to generate a new $K\alpha$. This simulation was run 1000 times, generating 1000 $K\alpha$. The minimum reliability score generated was $K\alpha = -0.11$ and the maximum reliability score was $K\alpha = 0.09$. This 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.

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

Out of the 76 participants, 20 participants were not included in the following analysis. Eleven participants were removed for not meeting the threshold for catch trial performance (as detailed above), 4 participants were excluded because they did not press any buttons during the entire study, suggesting 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 s 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 s (SE = 0.23) for vertical percepts, while the mean button press duration was 2.96 s (SE = 0.21) for horizontal percepts. For trials where participants were instructed to hold vertical motion, the mean button press duration was 5.01 s (SE = 0.32) for periods where participants perceived vertical motion (consistent with the instruction) and 0.72 s (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 s (SE = 0.36) for perceiving horizontal motion (consistent with the instruction) and was 1.48 s (SE = 0.20) for perceiving vertical motion (inconsistent with the instruction; Figure 5). To supplement the analysis of mean button press durations, we also examined the mean number of button presses (Figure 5). In general, the mean number of button presses shows the same overall pattern of results as the mean button press durations.

A 3 x 2 repeated measures ANOVA comparing mean button press durations by instruction type (change, hold vertical, hold horizontal) and perceptual state (vertical, horizontal) revealed a main effect of perceptual state, $F(2,55) = 15.17$, $p < .001$, where vertical percepts tended to last longer than horizontal ones. In addition, there was an interaction between instruction type and perceptual state, $F(2,55)$ =

74.11, $p < .001$. To further explore the interaction revealed in the 3 x 2 repeated measures ANOVA, we followed up with a 2 x 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, $F(2,55) = 17.15$, $p < .001$, due to longer button press durations for vertical percepts. Importantly, there was a strong interaction, $F(2,55) = 79.27$, $p < .001$, where motion that was consistent with the instruction had longer durations than motion that was inconsistent with the instruction.

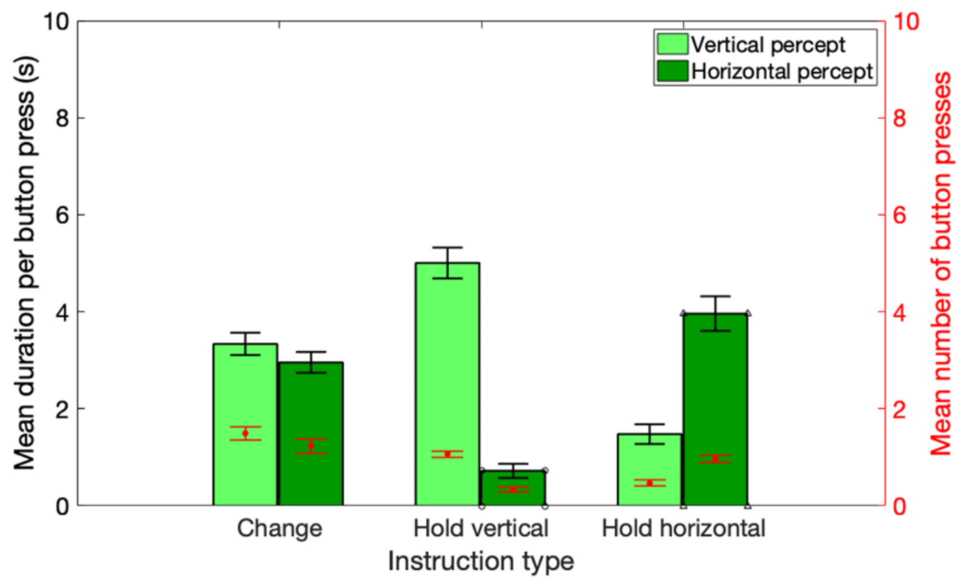

Figure 5. Results for Experiment 2. The mean button press durations and the mean number of button presses for each instruction type (change, hold vertical, hold horizontal) and perceptual state (vertical, horizontal) show longer button press durations for percepts consistent with the hold instruction (e.g., vertical percepts when instructed to hold vertical) compared to change durations, indicating that participants can control their perception of IAM.

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 s trials aren't 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 (M = 3.33 s, SE = 0.15) were longer than button presses in the change condition (M = 2.69 s, SE = 0.05), $t(952) = 5.00$, $p < .001$. 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 durations for inconsistent hold button presses (M = 2.32 s, SE = 0.14) were shorter than button presses in the change condition (M = 2.69 s, 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 s (*SD* = 0.61), but was 0.37 s (*SD* = 0.27) 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 of 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 in order to be included into the analysis. For the first criterion, 16 participants were removed, which occurred due 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 4 participants were removed due to not meeting this threshold. One additional participant was removed for having a saccade rate 2-3 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 5 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 reduce noise, and it was chosen at two frames to match the velocity sliding window of five frames. Saccades with angles between 45 and -45 degrees or between 135 and 225 degrees 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 to 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 to inconsistent with the instruction (e.g., perceiving horizontal motion when instructed to hold vertical). To create a measure of total saccade rate, we first summed vertical and horizontal saccade rates for each participant. A 2 x 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 total saccade rate. Additionally, there was no interaction between perceptual state and instruction type on total saccade rate, $F(2,68) = 0.408$, $p = .667$ (Figure 6A).

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 vertical and horizontal saccade rates for each participant. A 2 x 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 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 6B). 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.

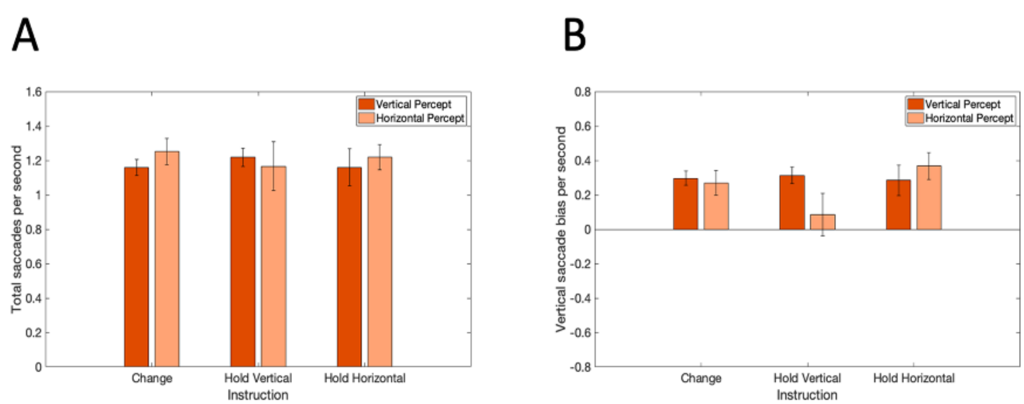

Figure 6. Saccades per second across the different perceptual states and instruction types for Experiment 2. A.) The total saccades per second for periods where participants reported perceiving vertical and horizontal motion for each of the instruction conditions. B.) The vertical saccade bias per second, 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.

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% (n = 21) of participants 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 7A). For the change trials, 35.71% (n = 20) of participants 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 non-categorizable (other) strategy, and 1.79% (n = 1) reported using rhythmic bodily movements (Figure 7B).

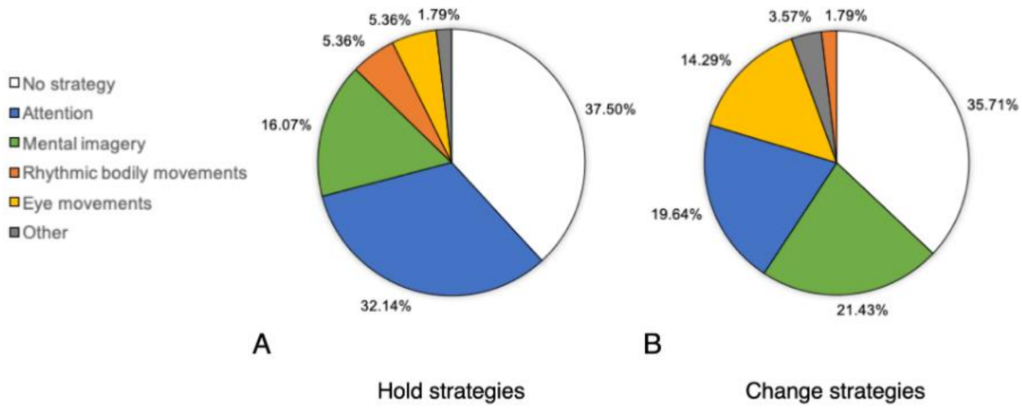

Figure 7. Survey results for Experiment 2. A.) The distribution of strategies that participants reported using when they were instructed to hold. B.) The distribution of strategies that participants reported using when they were instructed to change.

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 to 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 to 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 above). For this reason, we examined whether participants' subjective experience of using eye movements translated into differences in their overall saccade rates compared to participants who did not report using eye movements as a strategy only within the change condition. Of the 8 participants who reported using eye movements as a strategy for the change condition, one was removed from the eye movement analyses leaving us with 7 for the subsequent analyses. A two-sample t-test comparing the overall saccade rates for participants who reported using eye movements as a strategy (*M* = 3.50 per s, *SE* = 0.24) with participants who did not report using eye movements as a strategy (*M* = 3.77 per s, *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 to hold instructions. The 7 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 (*M* = 3.50 per s, *SE* = 0.24) compared to hold (*M* = 3.97 per s, *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 to 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 since participants are reporting their percepts dynamically throughout the trial (as opposed to a single report per trial). As mentioned above, despite the plethora of research showing that subjective control is possible across a variety of ambiguous or bistable stimuli, it wasn't *a priori* obvious that participants should be able to control their percepts in IAM due to some of IAM's properties that make it different from other polystable stimuli. For instance, it's possible that forming coherent percepts in IAM may be more demanding since participants have to first constrain from a large set of possible interpretations to perceive the particular motion (e.g., vertical or horizontal rebounding) in order to subsequently take the steps to control it, while other stimuli offer at least one or two interpretations "for free" 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 appear to be able to continue re-constraining 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 subjective control of polystable stimuli finds that eye movements, while 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 to 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 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 non-instructed percept, or doing a combination of both. From there, researchers may use stability durations to infer which of these strategies participants employed. Van Ee and colleagues (2005) suggest that, based on the pattern of durations that they found, when participants are holding percepts it's 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, 2007; Slotnick & Yantis, 2005; Windmann et al., 2006). What is left out of such considerations and mechanisms is: 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 to 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 to 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 to 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 in order to change the motion and to increase the duration of a desired percept in order to hold the motion, and the effect of control was greater in the change condition suggesting that participants may have been 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 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

8A & 8B). Given the substantial sample sizes collected from Experiments 1 and 2, we expect this pattern of results to be obtainable in future studies.

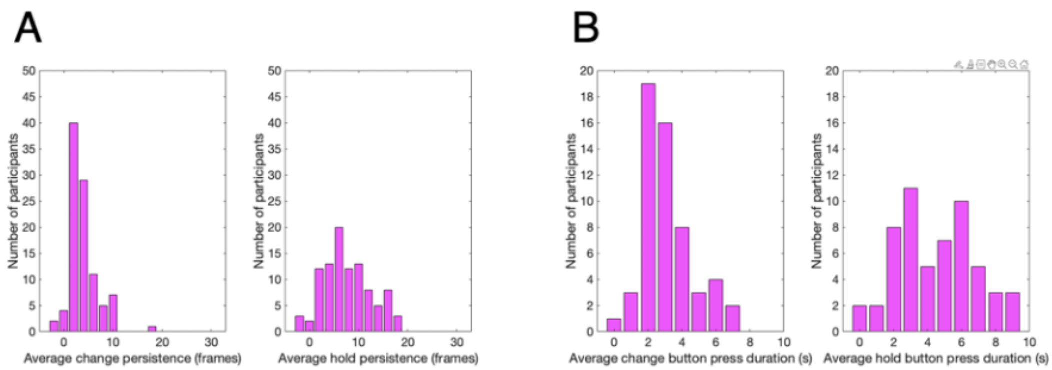

Figure 8. Individual differences in Experiment 1 and 2. A.) The distribution of mean persistence across trials in Experiment 1. The left histogram shows the distribution of persistence for change instructions, and the right histogram shows the distribution of persistence for hold instructions. B.) The 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).

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 due 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 before, some of its properties make it unclear whether it's appropriate to place in this category. For example, our question about whether individual differences arise due to (1) participants' ability to perceive coherent motion and (3) the decision criteria for reporting particular percepts in IAM are somewhat unique to IAM due to its high noise and high amount of visual transients compared to simpler polystable motion stimuli (such as apparent motion quartets).

This 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 subjectively control IAM, it's 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, in order 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 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 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) which the viewer experiences at least one of the interpretations without conscious effort, then 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 s for change (when collapsed across perceptual state) and 4.48 s for hold (collapsed across perceptual states consistent with the instruction). The mean absolute phase duration for apparent motion quartets was 7.2 s for change and 32.5 s for hold (for larger quartets). From this comparison, the durations are much shorter for IAM compared to apparent motion quartets. However, our trials were much shorter (only 10 s compared to 2 min 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 could help elucidate whether IAM should be considered in the same category as other polystable stimuli and whether it is easier or harder to control compared to 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 above, 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's 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're seeing isn't simply experimental demand. However, future research is needed to tease apart the role of decision making in the perceptual reports for IAM.

Conclusion

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 s trials. Even with this potentially more challenging task, participants were able to demonstrate substantial subjective control over their percepts of IAM.

Chapter III

Perceiving and controlling the countless interpretations of Illusory Apparent Motion

Polystable phenomena have long been of interest to perception researchers as the phenomena allow us to explore the constructive nature of perception. Past research has explored a plethora of polystable phenomena including, for instance: binocular rivalry, figure-ground rivalry (e.g., face-vase; Figure 1C), conceptual rivalry (e.g, duck-rabbit; Figure 1D), depth rivalry (e.g., Necker cube, Schroinger's staircase; Figure 1A and 1B), and motion-direction rivalry (e.g., structure-from-motion objects, apparent motion quartets). Across this variety of polystable phenomena, certain properties or features seem to be fairly consistent. First, when observers view these stimuli, they typically experience an initial interpretation automatically with no conscious effort. For example, observers of the Necker cube may initially interpret the object as front-view, rather than top-view (Figure 1A). Although some effort may be involved with reinterpreting the stimulus to experience an alternative interpretation, the initial organization of the stimulus into an interpretation tends to be automatic. Additionally, observers will, over time, experience competition between *two* interpretations of the stimulus, experiencing one interpretation of the object for a few seconds (e.g., seeing the duck-rabbit first as a duck) then having the object "switch" and experience another interpretation for a few seconds (e.g., seeing the duck-rabbit as a rabbit; Pöppel, 1997). Some objects have as many as four interpretations, such as the structure-from-motion cylinder (Hol, Koene, & van Ee, 2003). However, the majority of polystable phenomena involve two competing interpretations.

Recently, a new polystable illusion was discovered by Davidenko, Heller, Cheong, and Smith (2017) called *illusory apparent motion* (IAM). In this illusion, ambiguous apparent motion is generated from pixel arrays in which pixels are randomly generated across a series of frames with a relatively slow refresh rate (1 - 3 Hz). Interestingly, IAM has some features that seem to distinguish it from other polystable phenomena. One such feature is that observers may not experience an initial interpretation of the stimulus automatically. For instance, unlike the Necker cube example presented before, during informal presentations of IAM to conference or classroom audiences some observers simply report seeing “random” motion until they are verbally primed or intentionally try to see the stimulus as a coherent motion pattern (e.g., perceiving it as moving up-down-up-down).

Another feature distinguishing IAM from other polystable stimuli is that IAM is *maximally ambiguous*, affording potentially countless interpretations in contrast to the two interpretations most polystable stimuli have. Anecdotally, observers report experiencing many interpretations of IAM, such as translational, rotational, shear, expansion, and contraction. However, to date, research on IAM has explored the phenomena only in the context of translational and rotational motion (Davidenko et al., 2017; Heller & Davidenko, 2018). Although IAM research is still in its infancy, the maximal ambiguity of IAM offers a rich opportunity for researchers to explore the constructive nature of perception since there are many possible interpretations for observers to construct. (Along with the higher level and lower level influences that bias those constructions in a maximally ambiguous context [Heller & Davidenko, 2018].)

Perceiving IAM

As mentioned, IAM is a relatively new polystable phenomenon, and the first study was conducted by Davidenko and colleagues (2017). In the first set of studies exploring the perception of IAM, the authors examined the extent to which participants experienced IAM in the context of translational motion displays. In particular, observers completed a motion priming and persistence task in which participants were first presented with a series of priming frames that shifted in either a rebounding (e.g., up-down-up-down) or drifting (e.g., left-left-left) translational motion pattern. Importantly, real motion can be introduced into IAM displays by shifting a subset of the pixels (e.g., 80% of pixels) in a particular direction. Following the 8 priming frames, 23 additional frames were presented with 100% noise. All frames were presented at a 2.5 Hz refresh rate. During each trial, participants reported when they no longer experienced the initial motion pattern. This first examination of IAM revealed a distribution of motion persistence across participants in which the median persistence was 5.7 frames (or approximately 2.3 s) of, suggesting that participants experienced translational IAM into frames containing no motion signal. Additionally, when examining mean persistence for rebounding and drifting motion separately, the authors found that participants had longer persistence for rebounding compared to drifting trials, suggesting that participants have a 'rebound bias.' This general pattern of results was replicated with a second set of participants in this paper.

Following the first two experiments, the authors hypothesized that a differently shaped array, such as an annulus, would reduce the rebound bias (Davidenko et al., 2017). This led them to test a similar motion priming task, but this time rebounding rotational (e.g., clockwise-counterclockwise-clockwise) and drifting rotational (e.g., continuous clockwise) motion were presented in annulus displays. Importantly, this experiment found that participants had a median persistence of 7.5 frames (approximately 3 s), suggesting that participants were experiencing rotational IAM into frames containing 100% noise. The authors also found that the rebound bias was eliminated in annulus displays presenting rotational IAM.

Since this first paper by Davidenko and colleagues (2017), subsequent IAM studies have used similar displays (i.e., square or annulus) and general motion types (i.e., translational and rotational motion; Heller & Davidenko, 2018). Throughout the experiments in these studies, the main findings are that (1) participants experience translational and rotational IAM, and (2) participants exhibit a rebound bias, sometimes experiencing rebounding motion, even when they haven't been primed for it (Davidenko, Heller, Schooley, & McDougall, 2022).

Subjective control of IAM

Building on past findings on observers' ability to perceive IAM, additional research has explored observers' ability to subjectively control translational IAM (Allen, Jacobs, & Davidenko, 2022). Subjective control of IAM was explored because research on polystable phenomena has demonstrated widely that observers can subjectively control their interpretations of the stimuli, typically by changing (i.e., changing back and forth between two interpretations) and/or holding (i.e., maintaining a single interpretation for as long as possible) how the stimulus is perceived (e.g., Kohler et al., 2008; Liu et al., 2012; Suzuki & Peterson, 2000; Toppino, 2003; van Ee, van Dam, & Brouwer, 2005). However, it was unclear whether participants would be able to similarly exert perceptual control of IAM since IAM has some properties distinguishing it from typical polystable phenomena that have the potential to make subjective control more challenging. First, since IAM occurs in a context of pure noise, observers may not automatically experience an interpretation of coherent IAM (e.g., vertical rebounding). For stimuli, such as apparent motion quartets, the motion automatically appears to move either vertically or horizontally. In contexts of subjective control this could mean that observers have to self-generate an initial interpretation of the stimulus. Relatedly, it could also mean that if an observer is perceptually controlling IAM and loses their intended interpretation that they then have to again self-generate the interpretation; potentially re-self-generating the interpretation multiple times. Another potential difficulty is that IAM affords potentially countless interpretations which could make it more challenging for observers to subjectively control if alternative interpretations compete with the observer's intention.

In light of these questions, Experiments 1 and 2 explored whether participants could subjectively control translational IAM (Allen, Jacobs, and Davidenko, 2022). First, Experiment 1 uses a similar motion priming and persistence task as used by Davidenko and colleagues (2017). In this experiment, participants were first presented with a series of priming frames (3, 5, or 7) depicting either rebounding (e.g., up-down-up-down) or drifting (e.g., left-left-left) motion which then transitioned into a series of pure-noise frames (29, 27, or 25). On all trials participants were instructed to report once the initial motion pattern appeared to change. The main modification of the task to test subjective control was to present these trials in two different blocks of trials: (1) in the first block, participants passively viewed the motion and reported whenever the motion appeared different from the initial motion pattern, then (2) the second block instructed participants the subjectively control the motion by either changing (to any other motion pattern) or holding (maintaining the same motion pattern) the initial motion pattern. As mentioned in Experiment 1, the motion priming persistence task was used to explore whether participants could control IAM in a context where the initial interpretation didn't have to be completely self-generated.

Importantly, the results from Experiment 1 provided the first set of evidence that participants could control their perception of translational IAM. This was evidenced by participants' ability to shorten motion persistence during change trials and lengthen persistence during hold trials relative to the passive condition. This study also explored ‘No response trials’ (NRTs) in which participants did not press a button to report the motion appearing different from the initial motion pattern, suggesting that they presumably continued to see the primed motion throughout the trial. The NRTs provided additional evidence that participants were able to control the motion as participants had fewer NRTs during change trials and more NRTs during hold trials relative to the proportion of NRTs in the passive condition. A couple of things that are additionally noteworthy from the findings from Experiment 1 are, first, that a rebound bias was observed in both the passive and subjective control conditions. Rebounding trials had longer persistence and a greater proportion of NRTs overall. Additionally, the difference between the passive and change condition was greater than the passive and hold condition (in persistence and NRTs) suggesting that participants tended to be more successful at shortening their perception IAM rather than lengthening it.

Experiment 2 also explores the question of whether participants can control their perception of translational IAM. However, it extends these findings into an experimental paradigm that more closely resembles methods used in studies exploring subjective control of other polystable phenomena (based on the methods of Kohler et al., 2008). In particular, the study tested subjective control in a context where participants didn’t have the assistance of priming frames to generate the initial motion pattern. Instead, there were no priming frames, so participants had to generate the motion pattern. In addition, Experiment 2 focuses on rebounding motion since it seemed to be easier for participants to control compared to drifting (based on the persistence and NRT findings in Experiment 1), specifically vertical and horizontal rebounding motion. Finally, Experiment 2 focused on the contrast between the subjective control instructions to change and hold. Based on these modifications, Experiment 2 presented participants with pure noise trials where they changed or held (e.g., hold vertical) a particular motion pattern and had them report dynamically (by holding down one of two buttons) whether they were experiencing vertical rebounding, horizontal rebounding, or “other” at any time during each trial.

The findings from Experiment 2 again supported the hypothesis that participants can control their perception of translational IAM. In this case, this was evidenced by longer durations for percepts consistent with the instructed motion during hold instructions (e.g., reporting vertical rebounding when instructed to hold vertical motion). Taken together, Experiments 1 and 2 provide initial evidence that observers can subjectively control IAM even when observers may need to generate an initial interpretation, regenerate an interpretation multiple times if perceptual control is lost, and when the stimulus affords countless interpretations.

The current study

Collectively, previous IAM studies help to establish observers' ability to perceive translational and rotational IAM and to subjectively control translational IAM. However, this stands in contrast to, as was mentioned earlier, the idea that IAM affords potentially *countless* interpretations. Yet IAM research is still in its infancy, and only two general motion contexts (translational and rotational) have been explored thus far. This leaves open questions about observers' ability to experience the illusion outside of these contexts: Does IAM really have countless interpretations? Can observers experience IAM when viewing, for example, shearing, expanding, or contracting motion? If observers can perceive IAM in other motion contexts, does that also mean they have the ability to subjectively control the motion? The current study explores some of these open questions.

The main research questions Experiment 3 explores are: (1) Is it possible for participants to perceive and subjectively control motion patterns in IAM displays beyond translational rebounding and drifting motion patterns? (2) If so, how might participants' ability to perceive and/or control the motion differ by motion pattern? (3) And do participants experience more interpretations of IAM compared to other polystable phenomena? To test these questions, participants were tested on their ability to perceive and control translation, shear, rotation, and expansion-contraction. One of the benefits of the four general motion types used in this study is that they all have versions that can rebound or drift. Using the combined factors of rebounding compared to drift and the four general motion types, we tested participants on 14 different motion patterns (Table 1). (Note that rebound and drift motion can be distinguished also by motion steps per-cycle. For this reason, the name of this factor was simplified to 'motion steps per-cycle.')

	Motion steps per cycle	
General motion type	**Rebounding**	**Drifting**
Translation	1. Vertical rebound	7. Upward drift
	2. Horizontal rebound	8. Rightward drift
Shear	3. Vertical shear rebound	9. Up-down shear drift
	4. Horizontal shear rebound	10. Left-right shear drift
Expansion and contraction	5. Expansion/contraction rebound	11. Inward drift
		12. Outward drift
Rotation	6. Rotating rebound	13. Clockwise drift
		14. Counterclockwise drift

Table 1. The 14 motion types that were tested in Experiment 3. The motion types tested could be categorized based on the motion steps per cycle (rebounding and drifting motion) and general motion type (translation, shear, expansion-contraction, and rotation).

The study was divided into two, non-counterbalanced blocks. Following the methods of previous subjective control studies (Allen, Jacobs, & Davidenko, 2022; Kohler et al., 2008), participants first completed a passive block in which they were tested on their ability to perceive 14 different motion patterns in IAM. As mentioned in Experiment 1, participants always complete the passive block first in order to avoid possible carry over of knowledge that they may be able to control the motion from the subjective control into the passive block. Following the Passive block, participants completed a subjective control block in which they were tested on their ability to see the instructed motion pattern for as long as possible throughout the trial (also referred to later as the Hold block). For trials in both blocks, participants reported when they happened to perceive the instructed motion pattern by pressing down a key for as long as they were perceiving motion consistent with the instructed motion.

We predicted that, overall, participants would be able to perceive and control motion patterns beyond translational rebounding and drifting. This reasoning was based on the researchers' (AKA and ND) experience with demonstrating IAM to audiences in informal settings. In these informal settings, observers often reported the ability to see a variety of motion patterns (including shear, rotation, and expansion-contraction) beyond translational rebounding and drifting. In addition, it was predicted the results here would replicate patterns observed in previous IAM studies. In particular, we expect to observe a main effect of motion steps per-cycle, otherwise referred to as a 'rebound bias' in previous experiments, in which there tend to be longer durations for rebounding compared to drifting trials (Allen, Jacobs, & Davidenko, 2022; Davidenko et al., 2017; Davidenko et al., 2022; Davidenko & Heller, 2018). Based on the findings of Davidenko et al. (2017), we may expect the rebound bias to be weakened for rotational motion.

Also, based on the findings of Experiments 1 and 2, we predict that participants should be able to control their perception of IAM, and that subjective control would likely differ by motion type. Based on self-piloting the different motion types, it was predicted that overall translation would have the longest mean durations, followed by shear, expansion-contraction, and rotation. Part of the reason it was predicted that rotation would be more challenging is because, as mentioned above, previous IAM studies have tested rotation in annulus displays (Davidenko et al., 2017; Davidenko & Heller, 2018; Heller & Davidenko, 2018), but this study uses a square display which may be at odds with the motion path of rotating motion. This set of predictions was also based on piloting the motion types on the experimenters and research assistants (n = 10).

Finally, we also predicted that participants would be able to experience more interpretations of IAM relative to other polystable stimuli. In particular, we predicted that most participants would see around eight of the 14 motion types tested (with a predicted mean of around 7 interpretations) and that there would be a roughly normal distribution around this number.

In addition to the study's main research questions and predictions, the experiment also includes a couple of exploratory questions. In both blocks of trials, participants are asked at the end of each trial to rate how clear/vivid their experience of the motion was. This question was included to explore the relationship between motion types and clarity (e.g., are some motion patterns experienced as more clear/vivid) and between passive viewing versus subjectively controlling (e.g., is IAM experienced more clearly/vividly when observers are controlling the motion?). The Hold block included a second question asking participants to rate how difficult it was to see the motion. In this case, the question was included to explore whether participants' durations during control matched with their subjective effort of trying to control the motion.

Method

Participants

43 University of California, Santa Cruz (UCSC) undergraduates gave informed consent and participated for course credit. Participants had normal or corrected to normal vision. The study took approximately 45 minutes for participants to complete. The study was approved by the UCSC Institutional Review Board.

Stimuli

Stimuli were presented on a 22-inch LCD screen with a 60 Hz refresh rate. The majority of stimuli were created using Matlab (MathWorks, Natick, MA; see below for details). All stimulus presentation and data collection were controlled with Matlab. Participants viewed stimuli from a viewing distance of approximately 45 cm with no chinrest. All instructions presented were black 22- to 32-point Arial font on a gray background.

Based on the methods used by Davidenko and colleagues (2017) and those used in Experiment 1, first, a 560 x 560 random pixel matrix was created as a background array. Each pixel within the array had a 50% chance of being black or gray. The background array was fixed and was a sampling space for display arrays. Participants were presented only with the display array over a gray background and not with the background array. The display arrays were 140 x 140 pixel windows within the background array. These arrays were presented at a size of 15 cm by 15 cm (subtending approximately 18.92° x 18.92° visual angle) with a red fixation dot in the center of the display (Figure 9A).

During each trial, participants were first informed about a particular motion pattern to report about. Motion patterns were categorized along two factors: (1) motion steps per-cycle (i.e., rebound versus drift) and (2) general motion type (i.e., translation, shear, rotation, expansion-contraction). Combining these two factors of motion, participants were tested on 14 possible motion types. Assuming that the majority of participants were not familiar with these types of motion, in order to inform participants about how the motion type should appear, participants were presented with a brief demonstration consisting of four frames of a red square (or squares for shear) moving at 1.5 Hz (e.g., up-down-up-down). The red squares used in the demo were created in Microsoft Powerpoint and consisted of a 3-point line red square with no color fill over a gray background. When presented to participants, they were approximately the same size as IAM displays (subtending approximately 18.92° x 18.92° visual angle). After participants were presented with a demonstration of the instructed motion pattern, they were presented with 28 frames of random motion at a refresh rate of 1.5 Hz (each frame was presented for .667 s). This resulted in trials that were 18.68 s long.

For catch trials, participants were always presented with around 4.67 s of random motion, followed by 4.67 s of motion consistent (100% motion coherence) with the instruction, another 4.67 s of random motion, followed by 4.67 s of motion inconsistent (100% motion coherence) with the instruction. For the frames containing real motion, the motion was either generated by (1) shifting 100% of the pixels in the relevant directions or (2) by creating frames of motion in Microsoft Powerpoint using images of IAM. For instance, it was possible to generate up-down shearing motion in the pixel displays using a similar code as what generated random IAM. However, for motion such as expansion and contraction (e.g., inward contraction), there were limitations to coding the motion in Matlab, so the frames were created in powerpoint, then presented as images in the display during catch trials.

Procedure

The study consisted of two blocks of trials: *Passive* and *Hold*. As mentioned in previous experiments, the Passive block was always presented before the Hold block to avoid carry over of participants' knowledge about being able to control the motion. In the Passive block, participants were first informed about what IAM is and were presented a brief (6.67 s) demo of IAM with 100% noise. Prior to critical trials, participants were informed that they would be asked to report about certain types of motion in each trial, and that during the trial they should report when they happen to perceive that motion by holding down the '*g*' key. Participants were instructed to hold down the '*g*' key whenever they perceived the instructed motion and to do nothing when they happened to perceive any other pattern of motion.

At the beginning of each critical trial, participants were first presented with an instruction prompt reminding them to hold down '*g*' when seeing a specified motion pattern. For example, if the trial was for vertical rebounding motion, the prompt read: '*On this trial, press down 'G' whenever you see vertical rebounding motio*n.' The prompt was identical for all passive trials, except for which motion type they were instructed to report about. Following the initial prompt, participants were presented with a brief (2.67 s) iconic example of the instructed motion type using red squares. The iconic examples were included before each trial to clarify the motion pattern participants were being instructed to report about. After participants were presented with the brief example, the instruction prompt reappeared, reminding participants what motion type to report about during the trial. Participants self-initiated the trial by pressing the space bar. During the trial, participants were presented with 18.68 s (28 frames) of IAM with 100% noise (Figure 9B). At the end of each trial, participants were asked about the clarity of their perception: "*During the time that you saw the instructed motion, how clear/vivid was the motion*?" A 1-8 likert scale was used, with 8 indicating "*extremely clear/vivid*" and 1 indicating "*not clear/vivid at all*". If participants didn't see the motion during the trial, they were instructed to input 0.

After completing the Passive block, the Hold block was presented. This experiment focused on the Hold block and didn't include a Change block like past IAM studies (Allen et al. 2022), because hold instructions only require participants to be informed about one motion type for the trial, rather than having to change back and forth between two specified motions. At the beginning of the hold block, participants were instructed that, at times, it may be possible for them to control the motion. The Hold block was identical to the Passive block, except that participants were instructed to try to see the instructed motion for as long as possible during each trial. Participants were again instructed to hold down the '*g*' key whenever they happened to perceive the instructed motion.

Similar to the passive trials, participants were presented with an instruction prompt before each critical trial. However, this time the prompt instructed participants to Hold the motion type for as long as possible, in addition to the prompt presented in the Passive block. For example, if the trial was for vertical rebounding motion, the prompt read: "*On this trial, try to HOLD vertical rebounding motion for as long as possible. Press down 'G' whenever you see vertical rebounding motion*." Participants were then shown the same iconic example as in the Passive block, and the instruction prompt reappeared before the trial. Again, participants self-initiated the trial by pressing the spacebar, and were presented with 18.68 s of IAM with 100% noise. For the Hold block, participants were asked two questions at the end of each trial. First, participants were presented with the same question about clarity and 1-8 rating scale that they were presented with in the Passive block. Then, they were presented with an additional question about the difficulty of seeing the motion: "*During the time that you saw the instructed motion, how difficult was it to see the motion?*" Again, participants reported using a 1-8 rating scale, with 8 indicating "*extremely difficult to see the motion*" and 1 indicating "*not at all difficult to see the* *motion (very easy)*". For both questions, participants were instructed to input 0 if they did not happen to see the instructed motion for that trial.

Within each block, there were 14 motion patterns that participants were instructed to try to see or hold (Table 1). As mentioned above, the 14 motion patterns were categorized by motion steps per-cycle (rebound and drift) and general motion type. Instructions for each of the 14 motion patterns were presented twice, resulting in 28 critical trials, and were fully randomized within each block.

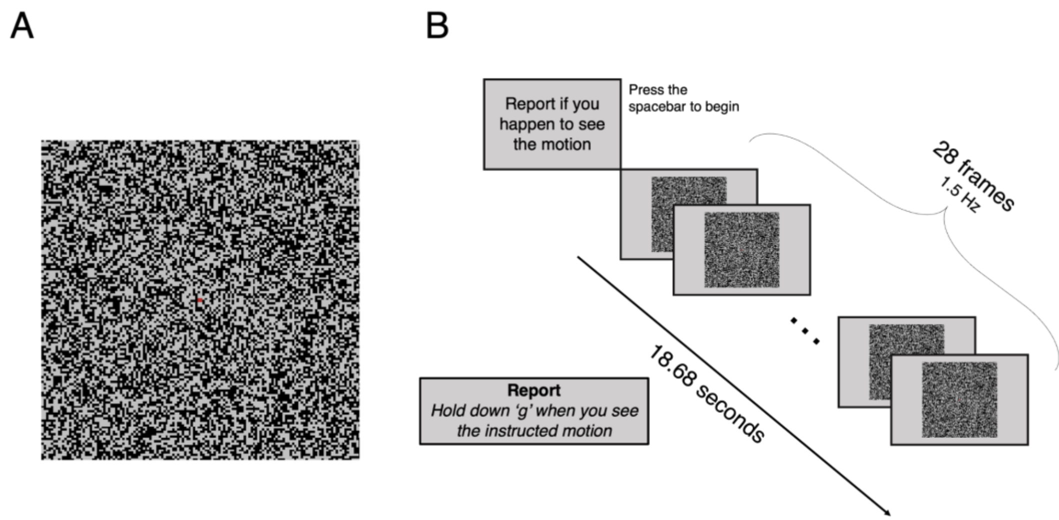

Figure 9. The stimulus and trial sequence used in Experiment 3. A.) A single stimulus frame with a red fixation dot. B.) An example trial sequence from the passive instruction block. During the passive block, participants were instructed to report if that happened to see a certain motion type (e.g., vertical rebounding motion). Each trial presented participants with 28 frames (18.68 s) of motion at 1.5 Hz. Participants held down 'g' on the keyboard to indicate when they perceived the instructed motion.

Catch Trials

In addition to the critical trials, participants were also presented with 14 catch trials within each block. Each of the catch trials consisted of portions of random (100% noise), consistent, and inconsistent motion. All catch trials began with 4.67 s (7 frames) of random motion, followed by 4.67 s of motion consistent with the instructed motion. For example, if participants were instructed to see vertical rebounding motion, the catch trial would present 7 frames of up-down-up-down motion with 100% motion coherence. This was then followed by another 4.67 s of random motion, then 4.67 s of motion inconsistent with the instructed motion. For example, if participants were instructed to see vertical rebounding motion, the catch trial would present 7 frames of rotating (clockwise-counterclockwise) rebounding motion with 100% motion coherence. Catch trials were randomized within the set of critical trials.

Catch trial performance was used to determine participant inclusion to the main analysis. Participants' performance during the period they were presented with consistent motion and inconsistent motion were examined. In order for participants to be included in the main analysis, they needed to have significantly different performance on the consistent portion compared to the inconsistent portion of catch trials.

Results

Similar to Experiment 2, the analysis here examines the durations that participants reported perceiving the instructed motion and focuses on the *total* *duration of button presses*. The total duration of button presses was calculated by first finding each instance a participant held down the space bar to indicate seeing the instructed motion type. Individual button press durations for each trial were then summed to calculate the total duration of button presses. Of the 43 participants who completed the experiment, 6 were excluded because they pressed no buttons throughout the entire study, and 2 were excluded for poor catch trial performance. The remaining 36 participants were included in all subsequent analyses.

Passive condition: Perceiving IAM

First, the mean total durations presented in Figure 11 demonstrate that participants were able to perceive all of the 14 motion types that we tested (all mean durations are significantly greater than zero). In order to determine which motion patterns participants were able to see, a 2-way within subjects ANOVA comparing motion steps per-cycle (rebound versus drift) and general motion type was applied to the passive condition. A main effect of motions steps per-cycle was revealed in which participants had longer mean total durations for rebounding (M = 6.56 s, SE = 0.68) compared to drifting (M = 4.19 s, SE = 0.50) trials, $F(1,34)$ =30.53, $p < .001$. There was also a main effect of general motion type in which some motion types, such as shear (M = 5.62 s, SE = 0.60) were overall perceived longer compared to others, such as expansion-contraction (M = 3.52 s, SE = 0.59), $F(3,102)$ = 9.18, $p < .001$. There was also an interaction observed between the two factors such that the rebound bias was more pronounced for some motion types (e.g., translation) and reduced or eliminated in other conditions (e.g., rotation), $F(3,312) = 6.15$, $p < .001$ (Figure 10A).

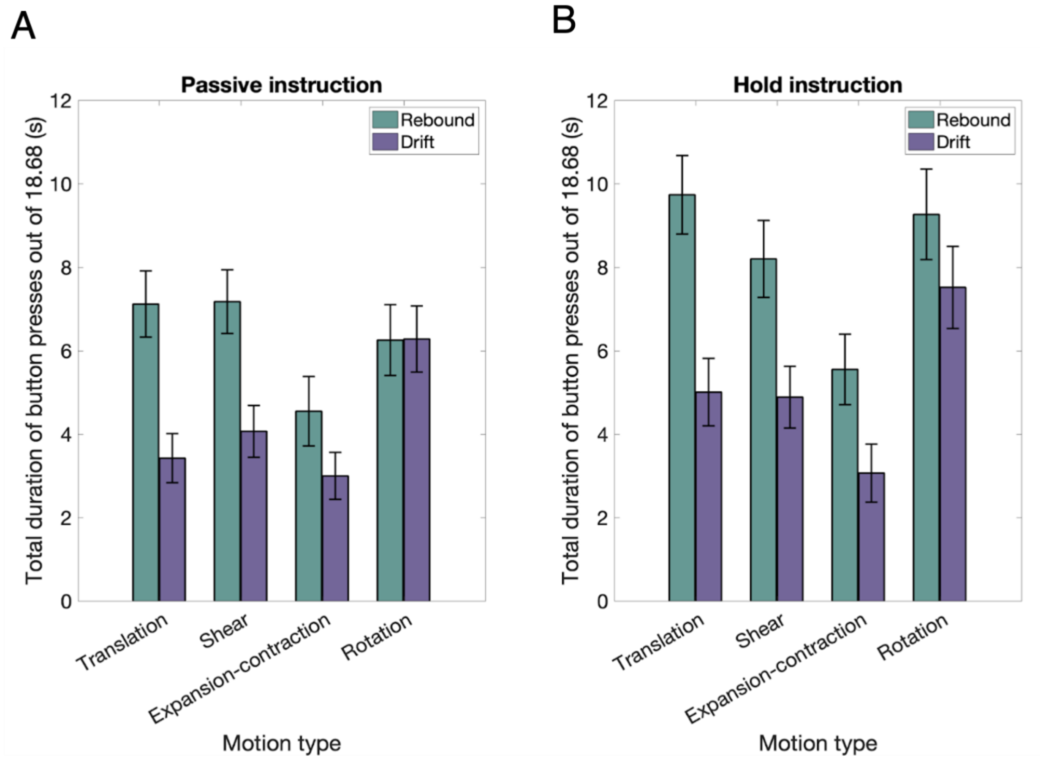

Figure 10. A.) The mean total duration of button presses for the passive condition. Overall, participants were able to see all of the tested motion types. B.) The mean total duration of button presses for the hold condition.

To gain a better understanding of the main effect of general motion type, a series of pairwise t-test comparisons of the general motion types were performed. The series of comparisons revealed that the mean total durations for expansion-contraction ($M = 3.52$ s, $SE = 0.59$) were significantly lower compared to translation ($M = 5.27$ s, $SE = 0.59$), $t(34) = 4.21$, $p < .001$, shear ($M = 5.62$ s, $SE = 0.60$), $t(34) = 4.15$, $p <$

.001, and rotation (*M* = 6.27 s, *SE* = 0.75), $t(34) = 4.38$, $p < .001$. No other comparisons were significant.

The mean total durations in the above analysis give a general sense that participants as a group were able to see the motion as categorized by the main factors: motion steps per cycle (rebound and drift) and general motion type (translation, shear, expansion-contraction, and rotation). However, what about the individual 14 motion types that were tested (Table 1)? To explore this in more depth, each of the 14 tested motion types were examined to get a sense of how well participants were able to see each one (Figure 11). From examining the means of the 14 motion types, it can be observed that, overall, the rebounding versions of the motion types tended to have longer mean durations. In particular, vertical shear rebounding (*M* = 7.82 s, *SE* = 0.88) and vertical translation rebounding (*M* = 7.79 s, *SE* = 0.79) motion had the longest mean durations. However, among the drifting motion types, rotating motion, such as clockwise drift (*M* = 6.36 s, *SE* = 0.89) and counterclockwise drift (*M* = 6.20 s, *SE* = 0.90), had mean durations comparable to rebounding motion types. Some of the more challenging motion patterns for participants to see were rightward drifting motion (*M* = 2.60 s, *SE* = 0.55) and inward drifting motion (*M* = 2.78 s, *SE* = 0.59) which had the shortest mean durations. Examining these patterns in a breakdown by participants revealed that, for the motion types with longer durations, more participants were able to experience perceiving the motion and tended to see the motion for relatively longer durations (Figure 12). For motion patterns that were more challenging for participants to perceive, fewer participants tend to experience these motion patterns and those who do perceive them tend to report doing so for shorter durations.

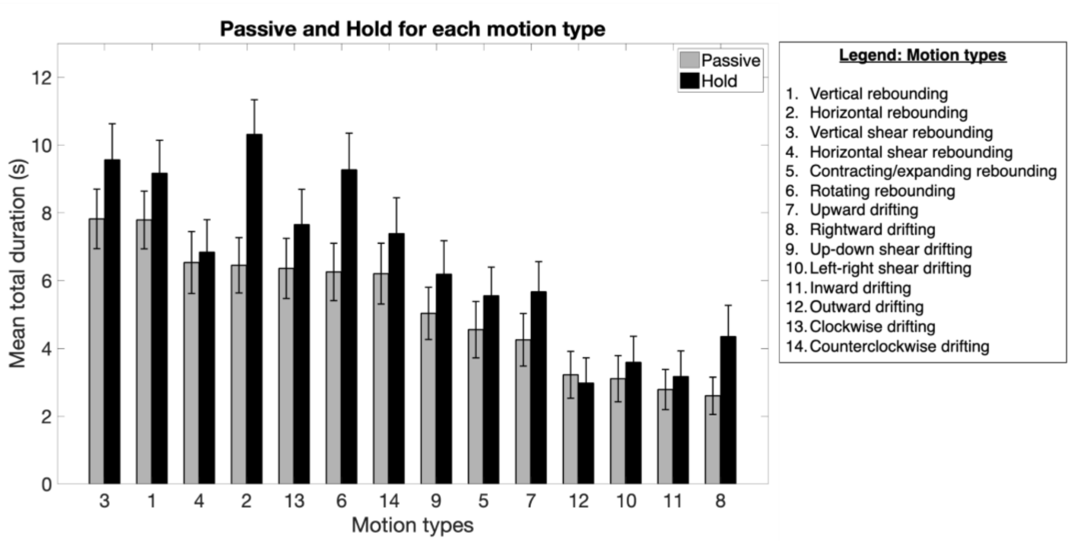

Figure 11. The mean total durations broken down by each of the 14 tested motion types. The gray bars represent mean total durations during the passive condition, and the black bars represent mean total durations during the hold condition. The x-axis is sorted (from left to right) by the motion types that had the longest to the shortest mean durations during the passive condition.

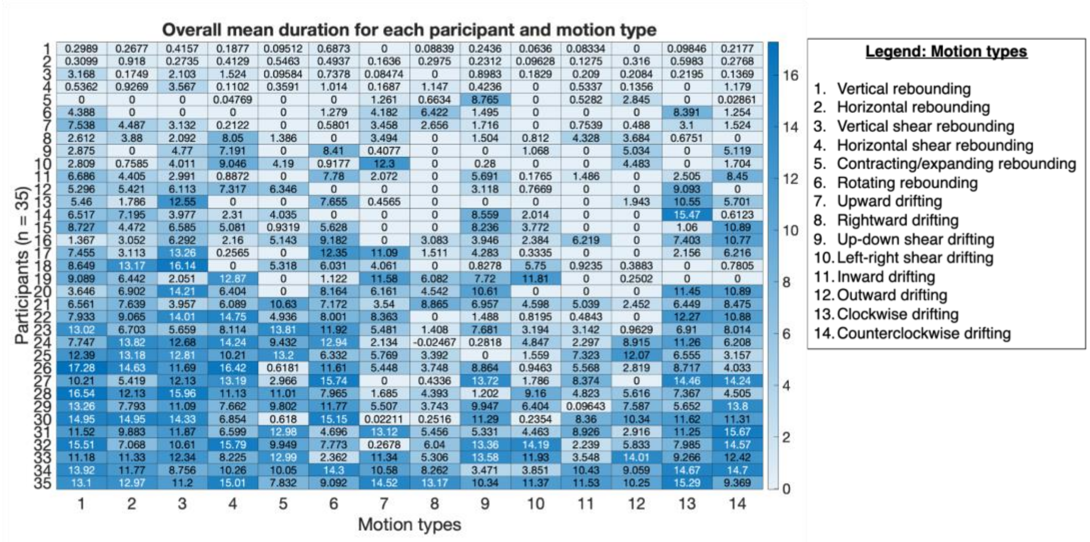

Figure 12. The mean total durations broken down by each participant (the y-axis) and the 14 motion types (the x-axis). Participants are sorted by those with the longest mean durations (across the 14 motion types) in ascending order. The darker shades of blue represent longer total durations and lighter shades represent shorter total durations.

So far these results suggest that, as a group, participants were able to see all 14 of the tested types of motion. However, a typical feature of polystable phenomena is that participants may have biases to see certain interpretations, while other interpretations may be more challenging to experience. Similarly, with IAM it's possible that some of the motion types were perceived by more participants compared to others. To calculate which of the motion types participants were able to see, it was counted as "seeing" if participants had a mean duration for a given motion type greater than zero. Based on this calculation, the motion types experienced by the largest proportion of participants were vertical translation rebounding (80%) and vertical shear rebounding (80%; Figure 13). The motion types experienced by the lowest proportion of participants were rightward translational drift (37%), left-right shear drifting (40%) and inward drifting (40%). Overall, rebounding motion types were seen by a higher proportion of participants (80% - 54%) compared to drifting (66% - 37%).

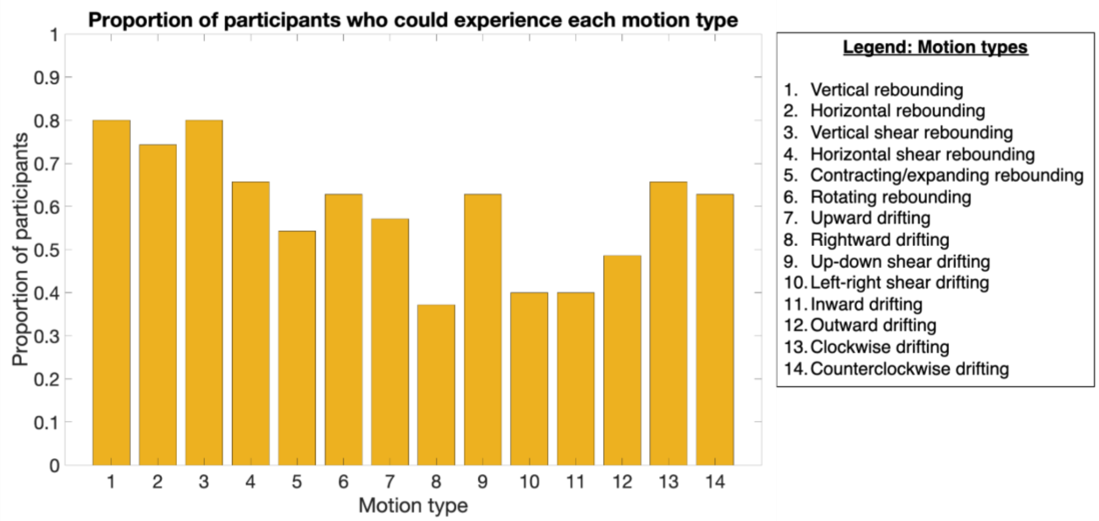

Figure 13. The proportion of participants that were able to perceive each motion type.

Another feature of polystable stimuli mentioned before is that most have only two competing interpretations. With IAM, because the stimulus is generated from pure noise the number of interpretations is potentially countless. Previous studies testing IAM suggest that participants can experience more than two interpretations in IAM (Davidenko et al., 2017; Davidenko, Heller, Schooley, & McDougall, 2022). However, it's unclear what the general range or upper limit of interpretations may be. To get a sense of how many of the 14 possible interpretations tested in this study participants could experience, the method mentioned in the previous paragraph was also used to determine whether participants could see a particular interpretation across the 14 interpretations tested (Figure 14). From this, there was a fairly wide range across participants of how many interpretations each participant could experience. The average number of interpretations participants could experience was 8.31 (*SE* = 0.75). There was a fair number of participants (*n* = *4*) who did not report seeing IAM for any of the tested motion types, as well as a fair number of participants (*n* = *4*) on the other end of the spectrum who reported seeing all 14 motion types.

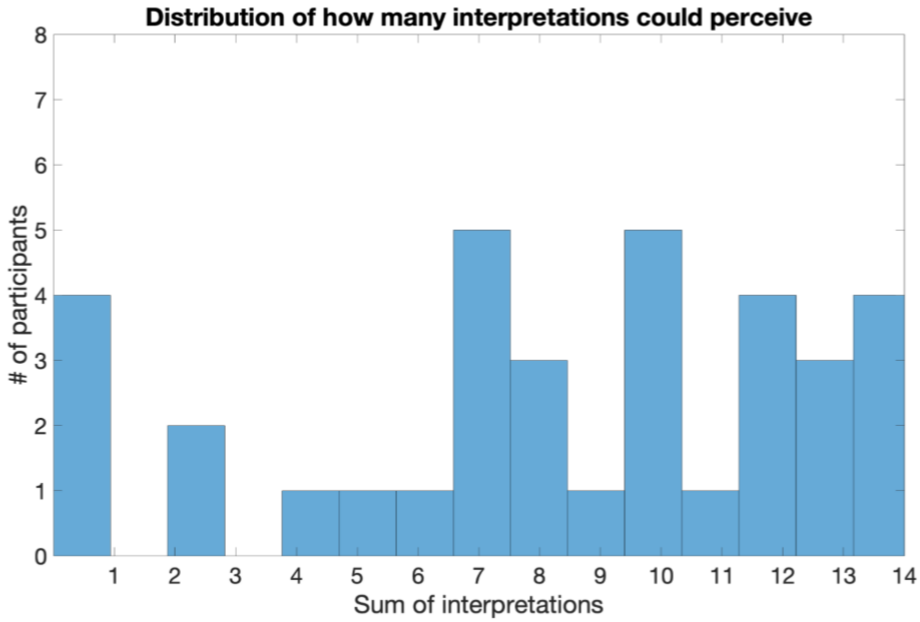

Figure 14. A histogram of the distribution of how many interpretations participants could perceive.

Subjective control of IAM: Comparing passive and active perception

The previous set of analyses explore participants' ability to see the motion types that were tested. The next set of analyses build on this by exploring participants' ability to subjectively control the motion. First, a 3-way ANOVA comparing block, motion steps per-cycle, and general motion type was used to compare mean total durations (Figure 10A and 10B). Importantly, there was a marginal main effect of block with slightly longer durations for Hold (M = 6.55 s, SE = 0.74) compared to Passive (M = 5.21 s, SE = 0.54), $F(1,34) = 4.10$, $p = .051$. There was a main effect of motion steps per-cycle in which rebounding trials (M = 7.51 s, SE = 0.67) had longer total durations compared to drifting (M = 4.66 s, SE = 0.53), $F(1, 34) = 45.42$, $p < .001$. There was also a main effect of general motion type such that some general motion types, such as rotation (M = 7.19 s, SE = 0.76), had longer total durations compared to others, such as expansion-contraction (M = 3.71 s, SE = 0.55), $F(3,102) = 20.23$, $p < .001$. There was an interaction between block and motion steps per cycle such that the difference between rebound and drift was greater when participants were holding (M_{diff} = 3.33 s, SE_{diff} = 0.43) compared to passively viewing the motion (M_{diff} = 2.37 s, SE_{diff} = 0.53), $F(1,34) = 4.40$, $p = .044$. There was additionally an interaction between block and general motion type such that the amount that participants were able to increase mean total durations was greater for some motion types, such as translation (M_{diff} = 2.10 s, SE_{diff} = 0.10) compared to others, such as expansion-contraction (M_{diff} = 0.38 s, SE_{diff} = 0.05), $F(3,102) = 4.20$, $p = .008$. Finally, there was an interaction between motion steps per-cycle and general motion type in which the difference between rebound and drift was greater for certain motion types, such as translation (M_{diff} = 4.21 s, SE_{diff} = 0.07) compared to others, such as rotation (M_{diff} = 0.86 s, SE_{diff} = 0.22), $F(3,102) = 6.05$, $p < .001$. No three-way interaction was observed.

To explore the difference between the Passive and Hold condition, a 2-way ANOVA comparing the difference in mean duration (Hold minus Passive) for motion steps per cycle (rebound, drift) and general motion type (translation, shear, expansion-contraction, rotation) found a main effect of motion steps per cycle in which the difference in means was greater for rebounding (M_{diff} = 1.88 s, SE_{diff} = 0.77) relative to drifting (M_{diff} = 0.93 s, SE_{diff} = 0.63), $F(1,34) = 4.40$, $p = .044$. Additionally, there was a main effect of general motion type where certain general motion types, such as translation (M_{diff} = 2.10 s, SE_{diff} = 0.77), the overall difference in means was greater compared to other motion types, such as expansion-contraction (M_{diff} = 0.38 s, SE_{diff} = 0.62), $F(3,102) = 4.20$, $p = .008$. There was no interaction between the two factors.

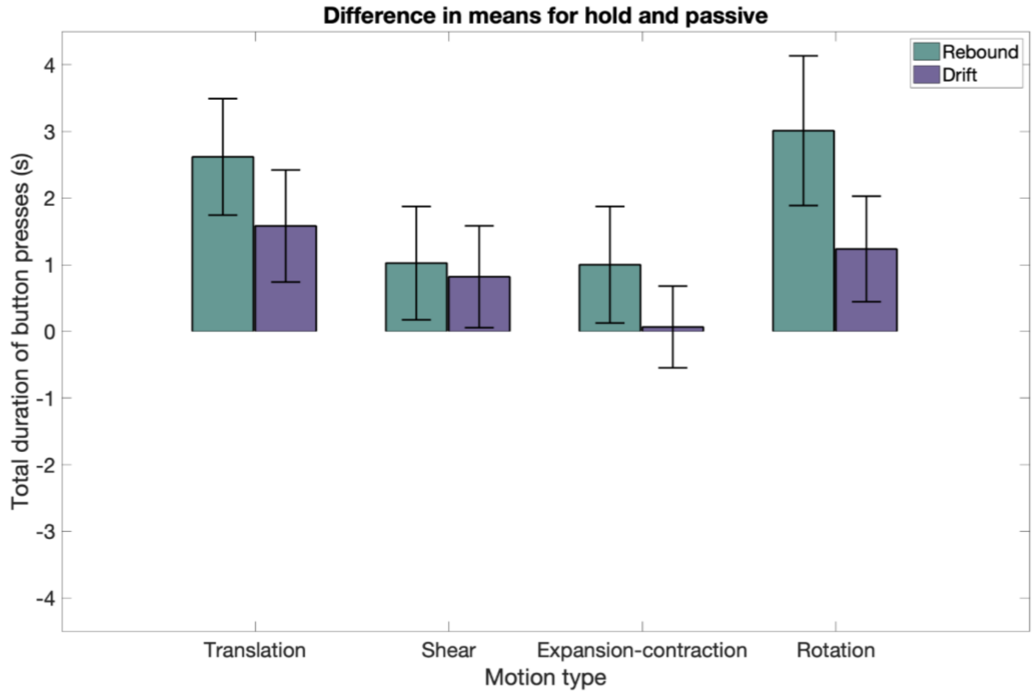

Figure 15. The difference in means for the hold and passive conditions.

The interactions between block and motion steps per cycle, and block and general motion type in the previous 3-way ANOVA suggest that participants were able to subjectively control some of the motion types that were tested. To examine which of the motion types participants were able to control, the mean total durations from the passive condition were compared with the hold condition for each of the 14 motion types in a series of t-tests (Figure 11). Interestingly, the series of comparisons revealed that participants were able to control only two out the the 14 tested motion types: horizontal rebounding (M_{diff} = 3.86 s, SE_{diff} = 0.21), $t(34) = 4.25$, $p < .001$, and rotating rebound (M_{diff} = 3.02 s, SE_{diff} = 0.23), $t(34) = 2.68$, $p = .011$. (Note that we checked whether this finding was based on participants' catch trial performance and re-ran the t-tests comparisons, but only for participants (n = 18) with above median performance on the catch trials, and the same pattern of results was obtained.) Examining a breakdown by-participant of the amount that participants were able to increase mean durations in the hold condition relative to the passive condition revealed that, for the two motions that participants were able to control, there were generally more participants able to increase their durations and increased durations were longer than other motion types (Figure 16).

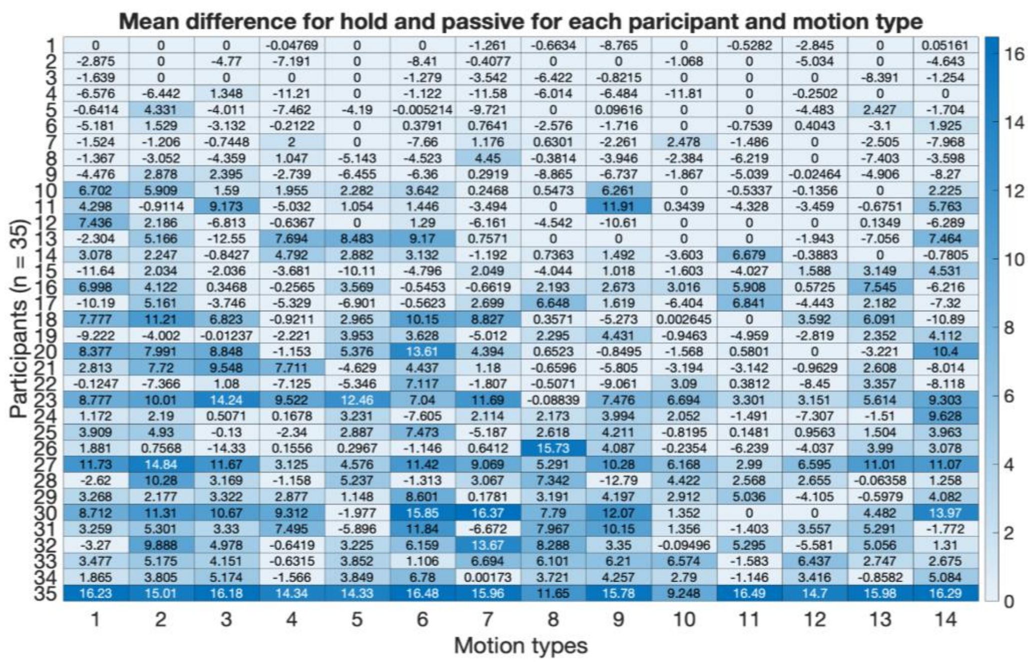

Figure 16. The mean difference between hold and passive is broken down by each participant (the y-axis) and the 14 motion types (the x-axis). Participants are sorted by those with the largest difference in mean durations (across the 14 motion types) in ascending order. The darker shades of blue represent larger differences between hold and passive (i.e., better hold performance).

Clarity ratings

As mentioned previously, at the end of each trial, participants rated (1-8 scale) how clear/vivid the motion appeared. First, to get a general sense of participants' clarity of perception during the passive condition, a 2-way ANOVA comparing motion steps per cycle (rebound and drift) and general motion type (translation, shear, expansion-contraction, rotation) was conducted. The ANOVA found a similar pattern of results as the mean total durations in the passive condition. Interestingly, participants clarity ratings also reflected a rebound bias: There was a main effect of motion steps per cycle where participants tended to rate rebounding (M = 3.79, SE = 0.16) as clearer than drifting motion (M = 2.67, SE = 0.14) , $F(1,34) = 36.26$, $p < .001$. There was also a main effect of general motion type with some motions, such as translation (M = 3.29, SE = 0.20), rated as clearer than other motions, such as expansion-contraction (M = 2.38, SE = 0.22), $F(3,102) = 8.12$, $p < .001$. There was an interaction where the difference between rebound and drifting ratings was greater for some motion types, such as translation (M_{diff} = 1.71, SE_{diff} = 0.01) compared to others, such as rotation (M_{diff} = 0.24, SE_{diff} = 0.09), $F(3,312) = 4.90$, $p = .002$ (Figure 17A).

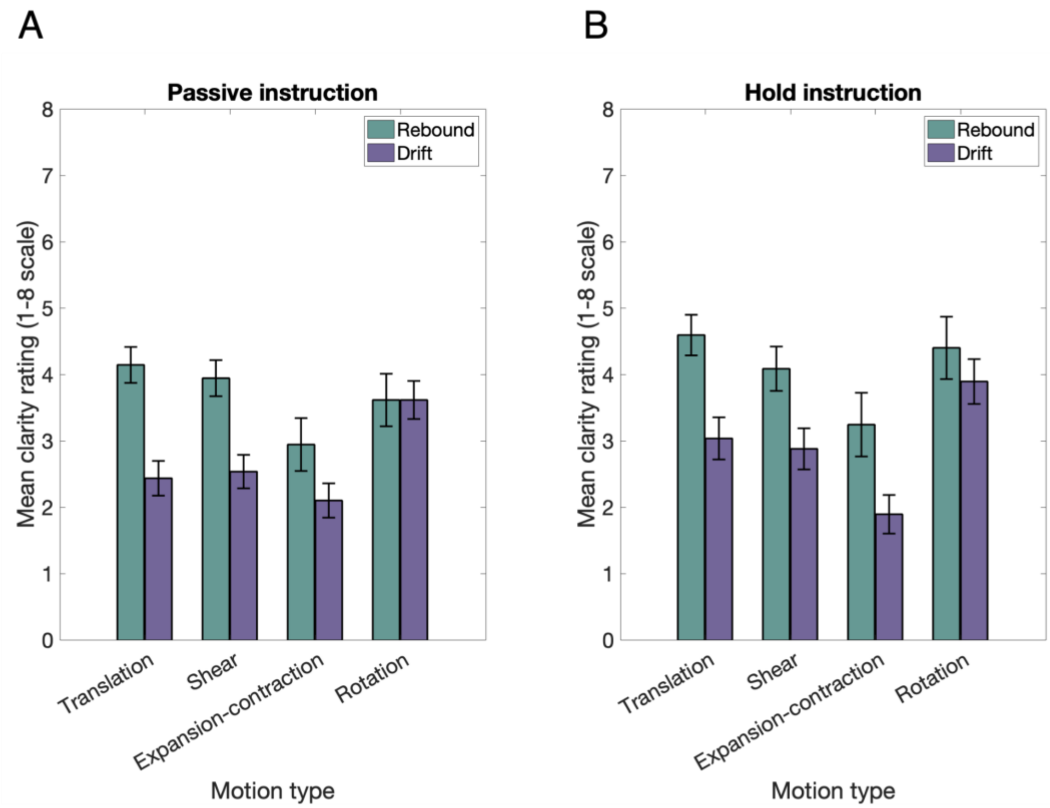

Figure 17. The mean clarity ratings for Experiment 3. A.) The mean clarity ratings for the passive condition. B.) The mean clarity ratings for the hold condition.

To explore whether participants' clarity ratings were influenced by subjective control, a 3-way ANOVA comparing block (passive, hold), motion steps per cycle (rebound, drift), and general motion type (translation, shear, expansion-contraction, rotation) was conducted. The 3-way ANOVA revealed a similar pattern of results as the 2-way ANOVA: a main effect of motion steps per cycle, $F(1,34) = 40.79$, $p < .001$, and general motion type, $F(3,102) = 16.61$, $p < .001$, as well as a similar interaction between motion steps per cycle and general motion type, $F(3,102) = 3.20$,

p = .026. However, no main effects or interactions of block conditions were observed (Figure 17A and 17B).

The above ANOVAs provide a general sense of how participants rated the clarity/vivacity of motion when collapsed across the main factors and allows for the comparison in clarity between perceiving and controlling the motion. However, we also wanted to get a sense of how participants' clarity ratings, when viewing IAM, compared with their clarity ratings during catch trials for the 14 motion types individually. To explore this, the clarity ratings from catch trials and critical trials within each block (passive and hold) were compared. Ratings during critical trials were compared with catch trials since catch trials contained portions of 100% motion. The portions of real-motion serve as a relative baseline measurement for how clear portions of real-motion appeared to participants relative to only perceiving IAM. Passive and hold trials, along with the catch trials corresponding to each of the conditions, were analyzed separately. Overall, across both passive and hold conditions, participants rated catch trials as clearer (M = 6.34, SE = 0.07) compared to the critical trials (M = 3.30, SE = 0.08), $t(34)$ = 28.15, $p < .001$ (Figure 18A and 18B). Among the 14 motion types that were tested, the motion types with the greatest difference (maximum possible difference would be 8) between catch trial and critical trial clarity were not restricted to the passive or hold condition. The motion types with the greatest difference in clarity ratings from perceiving real-motion and IAM were: outward drifting motion during hold trials (M_{diff} = 4.91, SE_{diff} = 0.14), rightward drift during passive trials (M_{diff} = 4.89, SE_{diff} = 0.09), and inward drifting motion during passive (M_{diff} = 4.70, SE_{diff} = 0.02) and hold trials (M_{diff} = 4.56, SE_{diff} = 0.03). The motion types with the least difference between catch trial and critical trial clarity occurred in passive and hold conditions. In particular, the motion types with the least difference were: vertical shear rebounding during hold trials (M_{diff} = 1.40, SE_{diff} = 0.11), horizontal translational rebounding during hold trials (M_{diff} = 1.43, SE_{diff} = 0.09), and vertical translational rebounding during hold (M_{diff} = 1.50, SE_{diff} = 0.03) and passive trials (M_{diff} = 1.66, SE_{diff} = 0.08). Notably, the motion types with the least difference were all rebounding, while the motion types with the most difference were drifting.

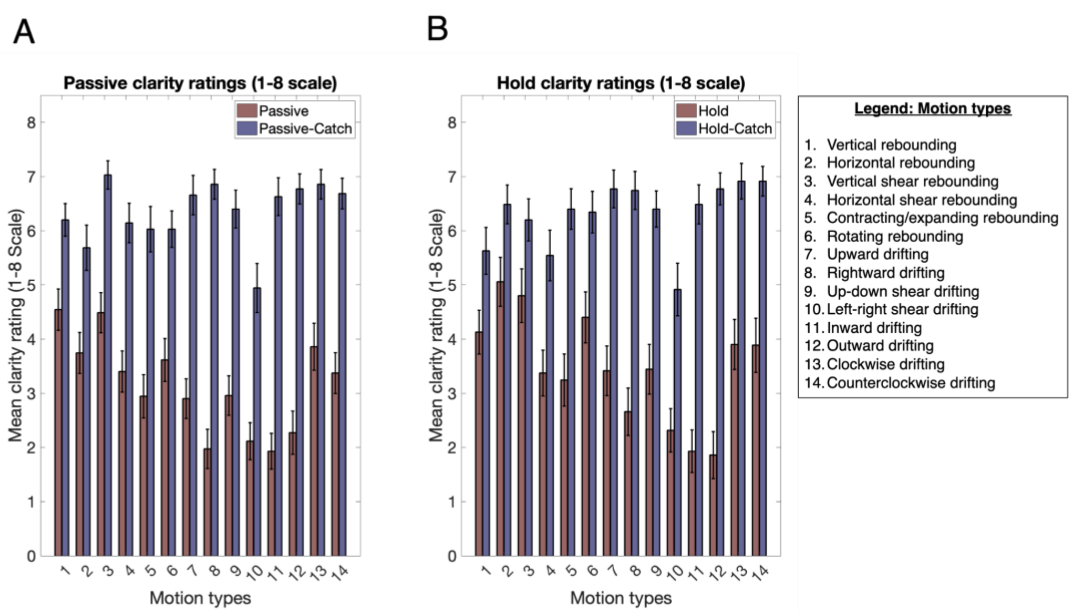

Figure 18. The mean clarity ratings for critical trials and catch trials for each of the 14 motion types. A.) The mean clarity ratings for critical and catch trials in the passive condition. Participants rated catch trials as more clear than critical trials. B.) The mean clarity ratings for critical and catch trials in the hold condition. Participants also rated catch trials during the hold condition as clearer that critical trials. Notably,

for both instruction conditions, participants tended to rate rebounding motion types as more clear than drifting motion types.

Difficulty ratings

As mentioned above, during the Hold block, participants were prompted to report (1 - 8 scale) about how difficult it was to see the instructed motion type. A 2-way ANOVA comparing the mean difficulty ratings across motion steps per-cycle (rebound and drift) and general motion type (translation, shear, rotation, and expansion-contraction), revealed no main effects of either factor.

Discussion

One of the first questions this study tested is whether it's possible for participants to perceive motion patterns in IAM beyond translational rebounding and drifting. It was predicted that participants would be able to perceive more than translational and rotational rebounding and drifting patterns. The results confirm this, showing that participants were able to perceive shear, expansion, and contraction. Participants were able to perceive all 14 of the motion types they were tested on.

When it came to exploring participants' ability to see the various motion types, it was predicted that translation would be the easiest motion pattern for participants to perceive, followed by shear, expansion-contraction, and rotation. The results did not match this prediction. Instead, the results found that translation, shear, and rotation had similar overall mean durations, suggesting that there were around the same level of difficulty, while expansion-contraction had the lowest mean durations, suggesting this motion type was the most challenging for participants to perceive. It was also predicted that, similar to previous IAM studies, that participants would exhibit a rebound bias, with longer durations for rebounding compared to drifting trials. The results matched this prediction, suggesting that the rebound bias generalizes beyond translational motion. Interestingly, an interaction between motion steps per cycle and general motion type was observed, suggesting that the strength of the rebound bias depends on the motion type. This finding is also consistent with previous IAM studies, which found that the strength of the rebound bias could be influenced and even eliminated when, for example, participants were presented with rotating motion in an annulus display (Davidenko et al., 2017).

Finally, the passive condition explores how many interpretations of IAM participants could experience. It was predicted that most participants would be able to experience more interpretations of IAM than are typically experienced with bistable phenomena. In particular, it was expected that most participants would perceive 8 interpretations of IAM and that the mean number of interpretations would be around 7.25. The results were not too far from these predictions. It was found that most participants experienced 7 interpretations of IAM, and the mean number of interpretations that participants experienced was 8.31. These results suggest that participants can experience many more interpretations of IAM compared to the two interpretations typically experienced in polystable phenomena.

The second set of predictions concerned the subjective control of IAM. First, it was predicted that participants would be able to control interpretations of IAM not previously tested (i.e., translation rebounding and drift). The results found that, overall, participants were marginally able to control the motion. Also, when comparing the difference in means, participants were overall more successful at holding motion when it was rebounding (compared to drift) and when holding certain motion types (e.g., translation). When passive and hold durations were compared for each of the 14 motion types, it revealed that participants were significantly successful at holding rebounding translational motion and rotational rebounding motion, suggesting that these were the easiest motion patterns for participants to control. These findings confirmed predictions that participants would be able to motion patterns aside from translational motion. The findings also confirmed predictions that certain motion patterns would be easier to control compared to others, such as rebounding being easier than drift. However, the pattern of the general motion types did not match the predictions. In particular, it was predicted that rotational motion would be the most difficult motion for participants to control. Instead, it turned out that (rebounding) rotational motion was one of the easiest for participants to control and, instead, expansion-contraction was the most challenging.

To supplement the behavioral findings, the study also explored participants' ratings of the clarity/vivacity of their perception of IAM on each trial. This question about clarity was included in the experiment to get a sense of how clear participants' experience of illusory motion was, especially compared to experiencing real motion. The results first examined clarity ratings during the passive condition. Interestingly, the pattern of results observed here align well with the pattern of results observed for the mean durations in the passive conditions. The relationship between these two measures was supported by a correlation analysis comparing the 14 tested motion types showing a strong relationship between the two, $r = .709$, $p < .001$. The hold condition showed a similar relationship between mean durations and clarity ratings, $r = .856$, $p < .001$. Another interesting finding from the clarity analyses was the difference between how clear participants rated trials containing real motion (catch trials) and trials where they reported perceiving illusory motion. Overall, participants rated the motion in IAM trials as less clear than in trials with real motion. However, the difference between the critical and catch trials varied by the motion type. Interestingly, motion types with longer mean durations (e.g., vertical shear rebounding) tended to have a smaller difference between IAM and real-motion trials compared to motion types with shorter mean durations (e.g., rightward drift).

Collectively the clarity/vivacity findings suggest that there is a relationship between mean durations and clarity ratings, which could be occurring for a couple of reasons. First, it's possible that clarity ratings reflect a perceptual difference between the different motion types in which easier to see and control motion types happen to be more perceptually vivid in participants' experience. If this is the case, it would suggest that when a motion type is easier to perceive, it's also clearer, and that clarity (for participants) could be nearly or as clear as trials containing real motion. Another possibility is that participants' perceptual experience of clarity is relatively stable, but that longer mean durations bias participants to rate the motion as clearer. If this is the case, then it could suggest that participants may have a poor sense of how clear the illusion is or are unclear about the nature of the question and use mean durations (consciously or unconsciously) to inform clarity ratings.

The hold condition included a second question asking participants to rate how difficult it was to see the motion. The results found no effects of difficulty ratings. One reason it's possible no effects were found in participants difficulty ratings is due to issues with how the question is worded. The phrasing for the question was for participants to rate "how difficult it was to see the motion." However, the intention was to get a sense of how difficult it was for participants to *control* the motion. Surprisingly though, it seems like if this is how participants were interpreting the question, we might expect the pattern of results to look similar to mean durations, but that wasn't the case. Another possibility is that there wasn't much difference between the passive and hold conditions insofar as participants were only able to control two of the motion types. The difficulty ratings could reflect participants' overall ability to control the motion. However, if this was the case, then one might expect the difficulty ratings to be fairly high. This wasn't the case, as the mean difficulty rating across all factors was 2.99 (out of 8). In short, it's hard to make sense of participants' difficulty ratings, and future research exploring subjective difficulty would be beneficial.

Individual differences and future directions

As mentioned in Experiments 1 and 2, previous research on IAM has consistently revealed individual differences in participants' ability to perceive (e.g., Davidenko et al., 2017) and subjectively control (e.g., Allen et al., 2022) IAM. For instance, Davidenko et al. (2017) found that some participants tended to generally experience more motion persistence and Allen et al. (2022) found variation in participants' ability to change and hold their perception (under the experimental conditions of Experiments 1 and 2).

Similar to these previous studies, the findings here demonstrated variability across participants when perceiving and subjectively controlling IAM. As mentioned in the introduction, previous IAM studies explored translational and rotating IAM. The findings here revealed similar individual differences in participants' ability to perceive IAM. Some participants reported an overall ability to perceive IAM, demonstrated through longer mean durations and for a larger number of the tested motion types, and some participants reported an overall inability to perceive IAM, demonstrated through short mean durations for fewer of the tested motion types. When it came to subjectively control, even though overall participants were only able to control two out of the 14 motion types that were tested, there was observable variability in the amount that participants were able to increase the mean durations in the hold condition. In particular, some participants demonstrated an overall ability to control the motion across the 14 motion types, evidenced by their ability to increase their mean durations during the hold condition, relative to the passive condition, across more (or all) of the tested motion types. Conversely, some participants seemed to have an overall inability to hold the motion, showing little to no increase in their mean durations for many of the tested motion types. One benefit of this experiment is that previous claims about individual differences now extend previous findings into additional, newly tested general motion types (e.g., shear, expansion-contraction), suggesting that participants' abilities to perceive and control IAM generalize beyond translation and rotation.

An important limitation of the results presented in this paper is that the motion arrays presented to participants were *square*. Past IAM studies suggest that the boundaries of the display may bias participants to interpret the motion in certain ways (Davidenko et al., 2017). For instance, annulus displays may bias participants to perceive rotating motion, as opposed to shearing motion. If the same experiment were run using annulus displays rather than square displays, it would be fair to expect different motion types to be easier or more challenging for participants to perceive and subjectively control. Now that this study provides evidence that participants can experience a broad scope of motion types, future research could explore how the different motion types interact with display boundaries.

Even though the current study suggests that participants can experience more interpretations of IAM compared to other polystable phenomena, what remains unclear is the extent that participants might experience spontaneous competition from alternative interpretations. Some previous research on polystable stimuli suggests that knowledge of the multiple interpretations of the stimulus may be important for observers to experience competing interpretations of the stimulus (e.g., Rock, Hall, & Davis, 1994). For this study, we informed participants prior to each trial about how the instructed motion type should generally appear. Given that participants were informed about 14 motion types in this study, it’s not clear in previous IAM studies where participants are not informed about additional possible interpretations whether or how frequently participants might spontaneously experience additional interpretations that also compete with study instructions (such as Experiment 2's instructions to change back and forth between vertical and horizontal rebounding motion).

Conclusion

The main aim of this experiment was to extend research of IAM as a maximally ambiguous stimulus and explore the scope of observers' perception and subjective control, beyond translation and rotation. The findings here suggest that observers can experience and control many interpretations of IAM, helping to support previous assumptions that observers likely experience more interpretations of IAM than other polystable phenomena. The findings also give a general sense of observers' ability to perceive and subjectively control the different motion types that we tested, giving a sense of potential biases that observers may have. As researchers this is helpful as future IAM research may opt to manipulate task difficulty or seek to explore certain interactions between higher and lower level processes that can bias interpretations of IAM.

Chapter IV

Quantifying low- and high-level factors that can bias perception of Illusory Apparent Motion

One of the main properties of polystable phenomena is the tendency for observers to experience automatic switching back and forth between different interpretations of the stimulus (Leopold & Logothetis, 1999). As such, polystable studies often present participants with relatively long display times (between 30 s to 2 min) in order to measure how switching occurs over time. Research has shown consistently that switching rates can be influenced by stimulus features (lower level factors) and cognitive states (higher level factors). In particular, switch rates can be influenced by either speeding up or by slowing down how frequently participants switch back and forth between interpretations. That switch rates can be influenced by stimulus and cognitive factors suggests that how participants experience polystable stimuli depends on how these lower and higher level factors come together (their relative strengths) and bias perception. The influence of specific factors is often not known since many may be included in a single viewing context.

Although it can be tricky to parse which factors are influencing and to what degree in a certain context, research has shown that certain stimulus and high-level factors can bias perception giving a sense of which factors may be at play. Under conditions of passive viewing, automatic switching can be driven by stimulus features associated with, for instance, stimulus geometry (e.g, Radilova et al., 2007), eccentricity (e.g., Suzuki & Peterson, 2000), stimulus density (e.g., Brouwer & van

Ee, 2006), stimulus complexity (e.g., Long, Toppino, & Kostenbauder, 1983) or stimulus timing (e.g., Brouwer & van Ee, 2006; Leopold, Wilke, Maier, & Logothetis, 2002). On the other hand, automatic switching can also be driven by cognitive factors, including for example: knowledge about the stimulus (e.g., Rock, Hall, & Davis, 1994), learning and memory (e.g., Brascamp et al., 2008; Harrison & Backus, 2010; Pastukhov, & Braun, 2008), overt action (e.g., Wohlschlager, 2000), attention (e.g., Chong & Blake, 2006; Paffen et al., 2006), and subjective control (e.g., Allen et al., 2022; Kohlers et al., 2008; Peloton & Solley, 1968).

Notably, subjective control is considered to be a higher level factor which can bias observers' perceptions of polystable phenomena. However, as mentioned above, perceptual biasing depends on the relative strength of the stimulus features and higher level factors in a given context. As such, subjective control is subject to observers' ability to control the stimulus in relation to the stimulus features. This makes subjective control easier in some contexts and challenging in others. Past research on subjective control has demonstrated that observers' ability can be influenced by stimulus features, including stimulus size (e.g., Kohlers et al., 2008; Long, 2003), density (e.g.., Brouwer & Van Ee, 2006), velocity (e.g., Liu et al., 2012), and timing (e.g., Mossbridge et al., 2013).

Although IAM is a relatively new polystable illusion, research suggests that observers' perceptions of IAM are similarly influenced by low- and high-level processes. For example, the findings from multiple IAM studies suggest that low level features, such as the configuration of the stimulus array (e.g., square or annulus;

Davidenko et al., 2017) or stimulus velocity (Heller & Davidenko, 2018) can influence how participants experience IAM. Other studies have highlighted the ability of higher level factors to bias the perception of IAM, such as subjective control (Allen et al., 2022) and motion priming (Davidenko et al., 2017). In short, how participants perceive IAM depends on the interaction between low- and high-level factors at play in the task. The interplay between low- and high-level factors on participants' perception of IAM raises a number of questions: (1) Which low and high level factors are important for perception of IAM? And (2) for the high and low factors that bias perception of IAM, how do they interact? For instance, could a low-level factor (such as motion coherence) interact with (either by facilitating or inhibiting) a higher level factor (such as motion priming or subjective control)?

The current study

Building past IAM studies, Experiment 4 explores the relationship between high- and low-level influences on the perception of IAM in the context of a motion nulling paradigm. The main question posed by Experiment 4 is: (1) Is it possible to quantify the influence of high and low level factors (e.g., subjective control, type of motion prime, proportion of motion signal) on the perception of IAM? (2) If so, to what extent do these factors contribute to biasing the perception of IAM? To test these questions, Experiment 4 was divided into two main parts: (1) a *threshold task*, and (2) a *motion nulling task*.

The critical part of the experiment for addressing the main research questions was the motion nulling task (although, note that the motion nulling task was the second task participants completed in the experiment). For the motion nulling task, to quantify the influence of high- and low-level factors on the perception of IAM, participants were presented with IAM displays containing two priming frames followed by two test frames (the study Method is based partially on Davideko et al. [2022]). Participants were primed with either rebounding (e.g., up-down, down-up) or drifting (e.g., right-right, left-left) motion. Following the two priming frames, the two test frames presented participants with one of five possible motion conditions. In some cases, the test frames contained motion moving in the same (consistent) motion as the priming frames (e.g. up-down followed by up-down, or right-right followed by right-right) and in other cases, the test frames contained motion moving in a motion nulling (inconsistent) direction relative to the priming frames (e.g. right-left followed by left-right, or down-down followed by up-up). In addition to manipulating the motion directions in the test frames, consistent and inconsistent motion were presented at two different motion coherence levels: one above the participant's perceptual threshold for detecting the presence of motion in IAM (estimated from the first part of the experiment, described below) and one below that threshold. A random (0% motion coherence) condition served as a baseline measurement for participants' perception of IAM.

In the motion nulling task, these stimulus conditions were explored in the context of both a passive and a subjective control condition. The main measure used to quantify the different factors were logistic curve fits based on the distribution of participants' mean proportion of prime-consistent responses. The passive condition focuses more on quantifying the contribution of lower level factors to the perception of IAM. Within the passive condition, the purpose of testing participants with consistent and inconsistent frames at above and below perceptual thresholds is to measure the strength of potentially nulling or facilitating participant's perception of IAM in terms of the motion coherence level. Since past IAM studies have demonstrated a robust rebounding bias (Allen et al., 2022; Davidenko et al., 2017; Davidenko et al., 2022; Davideko & Heller, 2018; Heller & Davidenko, 2018), manipulating the motion type additionally allows for the exploration of the strength of this lower level bias (again, quantified in terms of motion coherence). Experiment 4 also aims to quantify the strength of subjective control, a higher level factor that can contribute to biasing the perception of IAM (as demonstrated in Experiments 1-3). In the subjective control block, participants tried to subjectively control (hold) the motion under the same stimulus conditions, allowing us to quantify the strength of subjective control under these stimulus conditions.

For the motion nulling task, it was predicted, across the tested motion levels and type of test frames, that overall participants' prime-consistent responses would be distributed along a logistic curve. Based on a recent IAM study with a similar task design (Davidenko et al. 2022), we predicted that, for trials presenting participants with 0% motion in the test frames, two frames of priming would result in approximately 27% prime-consistent responses when primed with rebounding motion and approximately 22% prime-consistent responses when primed with drifting motion. For test frames containing prime-inconsistent, above threshold motion, we expect a relatively (compared to 0% motion test frames) much lower proportion of prime-consistent responses, with prime-inconsistent motion interfering with prime-consistent responses. For test frames containing prime-consistent, above threshold motion, we expect a relatively much higher proportion of prime-consistent responses, with prime-consistent motion facilitating prime-consistent responses.

Based on the findings from Experiments 1 through 3, we predicted that there would be a significant difference between the inflection points for the passive condition compared to the hold instruction, reflecting that the strength of subjective control, which should be able to (if control is successful) override some of the lower level factors biasing the perception of IAM.

One of the key manipulations for the motion nulling task is to present motion on the test frames above and below participants' perceptual threshold in IAM arrays. To do this, participants completed a threshold task prior to the motion nulling task. Each participant's threshold was used to customize the motion coherence levels used for the test frames in the motion nulling task. Before moving on to describe the motion nulling task, the threshold task itself raised questions worthy of exploration as this will be the first study to measure participants' thresholds for detecting the presence of motion in IAM. The main research questions raised by the threshold task are: (1) What are participants' thresholds for detecting the presence of rebounding motion in IAM? (2) What are participants' thresholds for detecting the presence of drifting motion in IAM? (3) And, are participants better at detecting the presence of one motion type over the other? These questions are also secondarily explored in the study. (Note that the procedure and outcomes of the pilot study are detailed in the next section labeled “Pilot study.”) The main prediction made for the threshold task was, based on previous research demonstrating a robust rebound bias for participants, that we expected to observe that participants would be able to detect the presence of rebounding motion at lower motion coherence levels than drifting motion.

Pilot threshold study

Since this is the first experiment to examine participants’ thresholds for detecting the presences of motion in IAM displays, an initial pilot study (*n* = 11) was conducted to gain a sense of (1) which motion coherence levels would be appropriate to capture most participants’ thresholds for detecting the presence of motion in IAM and (2) whether participants tended to experience mixed perceptions (e.g., seeing both illusory up motion and real motion signal shifting left). For the pilot study, participants were presented with brief IAM displays showing two frames of motion. For the pilot study, participants were presented with eight levels of motion coherence (20%, 30%, 35%, 40%, 45%, 50%, 55%, 60%) and two types of motion (rebound and drift). Each of the motion types had four variations each (e.g., rebounding up-down, rebounding down-up, drifting right-right, drifting left-left). Each of the eight motion types and eight coherence level combinations was presented 10 times, for a total of 640 trials. For each trial, participants reported the direction of motion that they perceived on the first, and then second frame transition. At the end of the pilot study, participants were given a brief questionnaire to assess whether they had experienced any mixed perceptions of IAM during the pilot study.

To determine each participant's threshold for detecting the presence of motion in IAM, we examined the distribution of responses to each of the motion coherence levels (20%, 30%, 35%, 40%, 45%, 50%, 55%, 60%) independently for rebound and drift motion trials. The distribution of expected responses was compared to the distribution of observed responses in a Chi-square comparison. The expected distribution of responses was based on the null hypothesis that participants' accuracy would be that of guessing across the 4 response options. The actual distribution of responses was based on each participant's actual number of correct and incorrect reports. In order for a participant to have above-chance performance, their Chi-square value for for a given motion coherence level needed to be above 3.84, and within each of the motion types, the lowest motion coherence level to be above that value was determined to be the participant's threshold (see the Results section for more details about this calculation).

The results from the pilot study found that, for participants with thresholds in the tested range, the mean threshold for rebounding was 41.25% motion coherence. The range of thresholds for rebounding motion was between 30% to 55% motion coherence. While the mean threshold for drifting was 44.29% motion coherence. The range of thresholds for drifting motion was also between 30% to 55% motion coherence. Based on these results, we decided for Experiment 4 to set 30% as the lowest motion coherence level and 70% as the highest level to test. Even though none of the pilot participants had thresholds as high as 70%, we wanted to use a large range to capture as many participants' as possible. In the range between 30% and 70%, the motion coherence levels were set to 10% increments, for a total of five motion coherence levels (30%, 40%, 50%, 60%, 70%).

Additionally, the questionnaire indicated that some (n = 5) participants at times weren't sure what to report because the motion they perceived wasn't possible with the four arrows (e.g., rotation, diagonal, shearing, expansion). One participant reported experiencing three motion directions at once and wasn't sure which to report. Overall, it appeared that participants were on occasion experiencing mixed percepts, but that it wasn't a widespread experience.

Method

Participants

54 University of California, Santa Cruz (UCSC) undergraduates participated for course credit. Participants had normal or corrected to normal vision. The study took approximately 70 minutes to complete and was approved by the UCSC Institutional Review Board.

Stimuli

Similar to experiments 1-3, all stimuli were presented on a 22-inch LCD screen with a 60 Hz refresh rate with a viewing distance of approximately 45 cm. All stimulus creation, presentation, and data collection was controlled with Matlab (MathWorks, Natick, MA). All instructions presented were black 22- to 32-point Arial font on a gray background. Participants observed stimulus arrays without a chinrest.

Stimulus arrays were generated following the methods of Davidenko et al. (2022). Each IAM frame was 140 x 140 pixels and consisted of 50% black and 50% dark gray pixels. The pixel shades were randomly assigned each time a new IAM frame was displayed. IAM frames were presented at a 1.5 Hz refresh rate (approximately .667 s), and the array size when presented was approximately 11 cm by 10.5 cm (subtending 13.93° x 13.31° visual angle).

During the study, participants were presented with two different IAM array configurations depending on the block. The first block, *the Threshold task*, presented participants with three IAM frames (one initial frame and two frames of motion), which generated two frame transitions (or a two-step motion sequence) for participants. As mentioned before, a motion signal can be added to IAM arrays by randomly selecting a proportion of the pixels within the array to shift 4 pixels in one direction. During the threshold task, all trials included some level of motion coherence, and there were five possible levels of motion coherence: 30%, 40%, 50%, 60%, 70%. The motion directions presented in the shifting pixels were of two general motion types: rebounding (e.g., up-down) and drifting (e.g., right-right). Each motion type had four possible motion patterns, with a total of eight motion patterns (Table 2). Each of the eight motion patterns were presented in combination with the five levels of motion coherence. Participants completed 5 trials for each motion pattern and motion coherence combination, resulting in a total of 200 trials which were used to determine participants' threshold for detecting the presence of motion in IAM (Figure 19).

The second type of IAM array was presented in the final two blocks of the study, *the Motion nulling of IAM task*. For these blocks, participants were presented with IAM arrays configured with two priming frames, followed by two test frames. The two priming frames presented the same set of motion types (rebound and drift) as the threshold task and always contained 80% motion coherence.

The two test frames that followed the priming frames had five possible conditions: (1) *prime-inconsistent* test frames presented 10% motion coherence *above* participants' threshold for detecting IAM, (2) *prime-inconsistent* test frames presented 10% motion coherence *below* participants' threshold for detecting IAM, (3) random (0% motion), (4) *prime-consistent* test frames presented 10% motion coherence *below* participants' threshold for detecting IAM, and (5) *prime-consistent* test frames presented 10% motion coherence *above* participants' threshold for detecting IAM. For prime-inconsistent test frames, the motion presented in the test frames also consisted of the motion types presented in priming frames (rebound and drift) but moved in a pattern to null the motion in the priming frames. For example, for a trial presenting rebounding right-left motion in the priming frames, the prime-inconsistent test frames presented rebounding left-right. For a trial presenting drifting right-right motion, then the prime-inconsistent test frames presented left-left motion.

For prime-consistent test frames, the motion presented in the two test frames was a continuation of the motion presented in the priming frames. For instance, if the priming frames presented rebounding up-down, then the prime-consistent test frames presented up-down motion. For a trial presenting drifting down-down motion, the prime-consistent test frames would present down-down motion. Participants were presented with 5 trials of each motion pattern and test frame condition, resulting in 432 trials, 216 for each sub-block, in the Motion nulling task (additional details below; Table 2).

Prime type	**Type of test frames** (prime-relative motion and motion coherence level)		
Rebounding motion Includes: 1. Up-down 2. Down-up 3. Right-left 4. Left-right	Prime-inconsistent (nulling motion)	Random	Prime-consistent
	Below threshold (-10%)	0% Motion	Below threshold (-10%)
	Above threshold (+10%)		Above threshold (+10%)
Drifting motion Includes: 1. Up-up 2. Down-down 3. Right-right 4. Left-left	Prime-inconsistent (nulling motion)	Random	Prime-consistent
	Below threshold (-10%)	0% Motion	Below threshold (-10%)
	Above threshold (+10%)		Above threshold (+10%)

Table 2. A breakdown of the two main factors (1) motion type and (2) type of test frames.

Procedure

The study used a within-subjects design with three blocks of trials. Prior to beginning the study, participants completed a series of practice trials containing two frame transitions of IAM presented with 80% motion coherence. In order for participants to begin the study, they had to correctly report the motion in both frames for three trials. If participants did not correctly report three trials after 20 practice trails, then they did not progress to complete any critical trials.

Once completing practice trials, participants proceeded to the first block, the Threshold task, which was a series of trials to determine each participant's threshold for detecting the presence of motion in IAM. For the threshold task instructions, prior to completing any trials, participants were first informed that there would be two frame transitions and that they should report what motion they perceived on the first, and then second frame transition using the arrow pad on the keyboard. Following this instruction, participants were presented with an example of an IAM array with two frame transitions and that contained 0% motion. Participants then were informed that some trials may be challenging, and that if they weren't sure about the direction(s) of the motion to make their best guess.

During threshold task trials, participants were presented with brief IAM displays depicting two frame transitions (two steps of motion) with five different levels of motion coherence (30%, 40%, 50%, 60%, 70%; Figure 19). Each motion type and motion coherence combination were presented five times and presented in a fully randomized order. The two frame transitions resulted in trials that were approximately 2 s long. At the end of each trial, participants reported using the arrow keys (up, down, left, and right) on the keyboard which direction the first and then second frame transition appeared to move. In order to proceed to the next set of blocks, the Motion nulling task, participants needed to achieve a threshold for detecting the presence of motion in IAM within the range of motion coherence levels that were tested (30-70%) for both rebounding and drifting motion patterns (see Results for details about how thresholds were calculated). The threshold for detecting the presence of motion in IAM that participants achieved independently for rebounding and for drifting trials were combined into a mean threshold for the Motion nulling task.

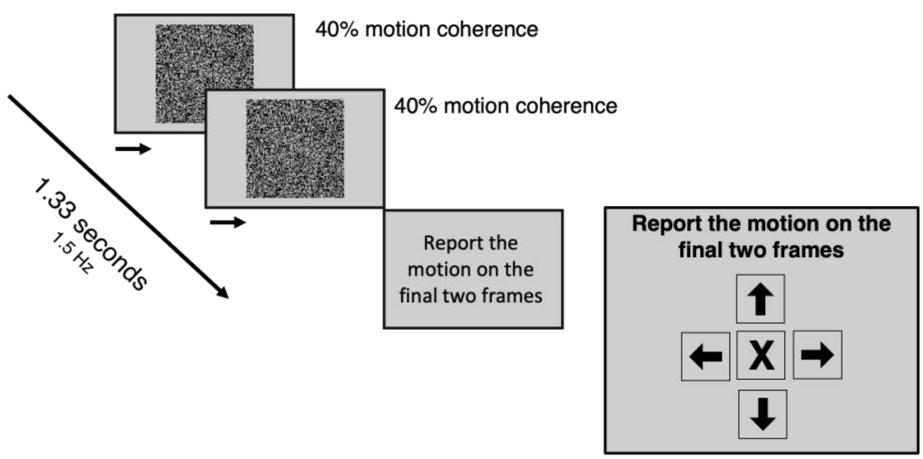

Figure 19. An example trial from the threshold task. In this example the participant would be presented with 40% motion coherence and report what they perceived in the display.

Following the Threshold task, participants completed the Motion nulling task which consisted of a *passive instruction* block and a *hole instruction* block. Following the procedures of past subjective control studies, participants always completed the passive block first (e.g., Allen et al., 2022; Kohlers et al., 2008). For the passive block instructions, participants were informed that they would be presented with IAM arrays containing two priming frames followed by two test frames and were shown a brief example trial. Similar to the Threshold task, participants were instructed to report the motion that they perceived on the final two frame transitions of the trial and to use the arrow keys on the keyboard to report the direction of motion.

During passive instruction trials, participants were presented first with a prompt to "*observe the motion*." Participants then self-initiated each trial by pressing the spacebar. During each trial, participants were presented with brief IAM displays depicting two priming frames, followed by two test frames (four steps of motion altogether). As mentioned above, two types of motion and five types of test frames were presented in these trials. Each motion type and type of test frame combination was presented five times and in a fully randomized order. Each presentation of IAM was approximately 3.34 s long. Again, at the end of each trial, participants reported the directions of motion that they perceived using the arrow keys on the keyboard (Figure 20).

Following the passive instruction block, participants completed a hold instruction block. The procedure and stimuli for the hold instruction block was identical to the passive instruction block, except for the following changes. First, the instructions that participants were given prior to critical trials informed that it may be possible for them to, at times, mentally control the motion presented in the IAM arrays. Participants were instructed to "*notice the initial pattern shown in the first two frames and then try to* <u>*hold*</u> *the pattern so that it continues into the final two frames*." Again, participants were instructed to report what they happened to perceive on the final two frame transitions using the arrows on the keyboard. Then, at the beginning of each trial, participants were presented with the prompt "*Try to* <u>*hold*</u> *the initial motion pattern"* before self-initiating the trial by pressing the spacebar. Finally, each motion type and type of test frame combination was again presented five times and in a newly fully randomized order.

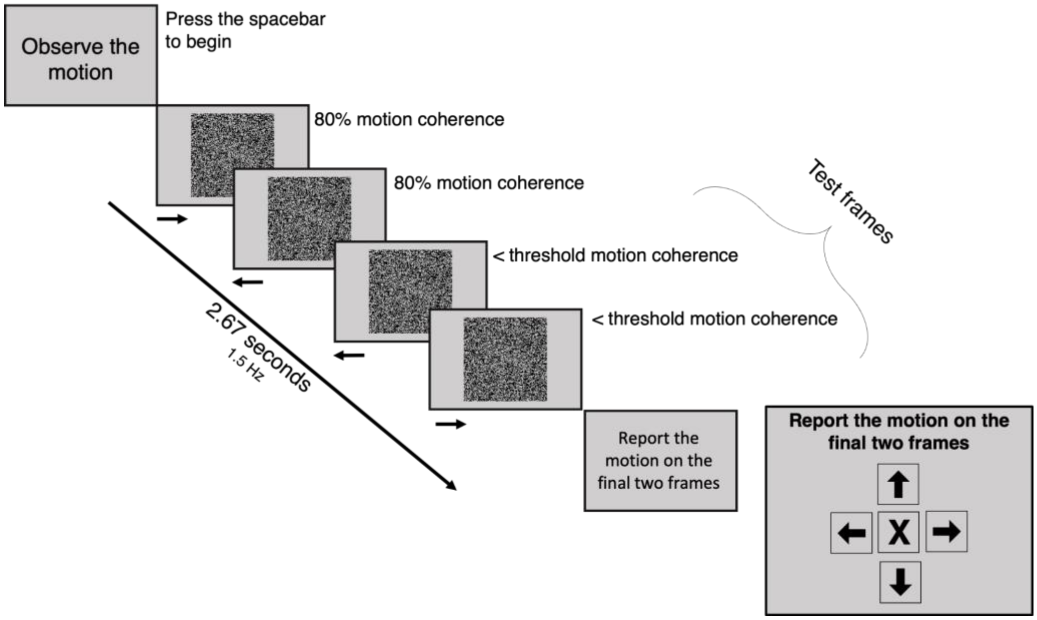

Figure 20. An example motion nulling trial in the passive block. The example depicts two rebounding priming frames, followed by two test frames with inconsistent motion below threshold.

Results

Thresholds: Detecting the presence of motion in IAM

This is the first experiment to measure participants' threshold for detecting the presence of motion in IAM arrays. To determine the threshold for detecting the presence of motion in IAM, we first examined the distribution of responses to each of the motion coherence levels (30%, 40%, 50%, 60%, 70%), separately for rebound and drift motion trials. For example, for rebound motion, we set up a table of expected and observed values for the four types of rebound motion (up-down, down-up, right-left, and left-right). The expected proportion of responses was based on a null hypothesis of complete guessing, which would result in equal distributions across the 4 response options, regardless of the motion type. In total, there were 20 rebounding trials for each participant at each coherence level, so the expected number of correct responses under the null hypothesis was 20/4, and the expected number of incorrect responses was 3*20/4. We computed the actual distribution of responses based on each participant's actual number of correct and incorrect reports. The expected and actual distributions were compared using a Chi-square analysis with 1 degree of freedom. In order for a participant to have above-chance performance, their Chi-square value at a given motion coherence level needed to be above 3.84. Within a given motion type, this was calculated for each motion level, and the lowest motion coherence level with a Chi-square value above 3.84 was determined to be the participant’s threshold.

Based on this criteria, 32 participants did not move on to the Passive and Hold tasks. Of these 32 participants, 24 participants met the threshold range for rebounding, but not for drifting motion. Only 5 participants met the threshold for drifting, but not for rebounding motion. And 3 participants did not have a threshold for either rebounding or drifting motion. Of the remaining 22 participants who did meet the threshold requirement, the mean threshold for rebounding was 50.91% (SE = 2.36) motion coherence and the mean threshold for drifting was significantly higher at 57.73% (SE = 2.07) motion coherence, $t(21) = 2.56$, $p = .018$.

Once participants moved onto the Passive and Hold tasks, their specific thresholds obtained for rebound and drift were combined into a mean threshold. The mean threshold was then used to calculate the ‘above threshold’ conditions, which added 10% motion coherence to the participant’s mean threshold, and ‘below threshold' conditions, which subtracted 10% motion coherence from the participant's mean threshold. Across participants, the average threshold used for the 'above threshold' and 'below threshold' calculations were 54.35% (*SE* = 1.78) motion coherence.

Motion nulling the perception and subjective control of IAM

22 participants met the threshold requirement. Of these 22 participants, one additional participant was removed as an outlier for low performance when accurately reporting the motion presented in test frames that were consistent with the primed motion and above threshold. 21 participants were included in all subsequent analyses of the Motion nulling task.

The main measure examined in the following set of analyses is the *mean proportion of prime-consistent responses* and is based on the two responses participants gave on each of the test frames that followed motion priming. Responses were considered prime-consistent if they were a continuation of the pattern established by the prime. For example, if a participant was primed with "up-down," then the prime-consistent response would be "up-down." Or, in the case of drifting, if a participant was primed with "right-right," then the prime-consistent response would be "right-right." For each participant, the mean proportion of prime-consistent responses obtained for the five different motion level conditions were used to calculate a logistic curve fit (with two fixed parameters and two parameters to the data). The point of inflection obtained for each participant's fit curve was the main measure used to compare factors in the following analyses. We also used the slope estimate to compare the relative strength of high-level and low-level factors in the perception of IAM.

A 2-way within subjects ANOVA was used to compare instruction (passive versus hold) and motion type (rebounding versus drift). The ANOVA revealed a main effect of instruction in which participants' mean inflection point for passive instructions (*M* = 24.64%, *SE* = 2.94) were significantly higher compared to hold instructions (*M* = 10.19%, *SE* = 7.11), $F(1,20) = 6.38$, $p = .020$. The role of subjective control, holding the motion, required 15.02% less motion signal than perceiving (passively viewing) IAM, suggesting that participants require an approximately 15% reduced motion signal to have comparable proportions of prime-consistent reports with passively viewing IAM. There was also a main effect of motion type where inflection points for drifting (*M* = 32.62%, *SE* = 4.72) were higher compared to rebounding (*M* = 2.21%, *SE* = 6.42), $F(1,20) = 22.35$, $p < .001$. There was no interaction between the two factors (Figure 21).

To examine whether the type of motion prime influenced participants' reports of prime-consistent motion on the test frames, the mean inflection points for rebounding and drifting motion were compared separately for the passive and hold conditions. For the passive condition, a paired samples t-test revealed that the inflection point for drifting primes (*M* = 41.24%, *SE* =4.00) was significantly higher than rebounding primes (*M* = 8.05%, *SE* = 4.51), $t(20) = 5.39$, $p < .001$, suggesting that the priming strength of rebounding motion is greater than drifting by a difference equivalent to 33.19% motion signal (Figure 21). In other words, participants would require around 33% more motion signal in drift trials to have comparable proportions of prime-consistent reports as in rebound trials. For the hold condition, a paired samples t-test revealed that the mean inflection point for drifting primes (*M* = 24.00%, *SE* = 6.55) was significantly higher compared to rebounding primes (*M* = -3.62%, *SE* = 9.21), $t(20) = 3.78$, $p < .001$, suggesting that the priming strength of rebounding motion was greater than drifting by a difference equivalent to 27.62% motion signal. In other words, participants would require around 28% more motion signal for drift trials to have comparable proportions of prime-consistent reports in rebounding trials.

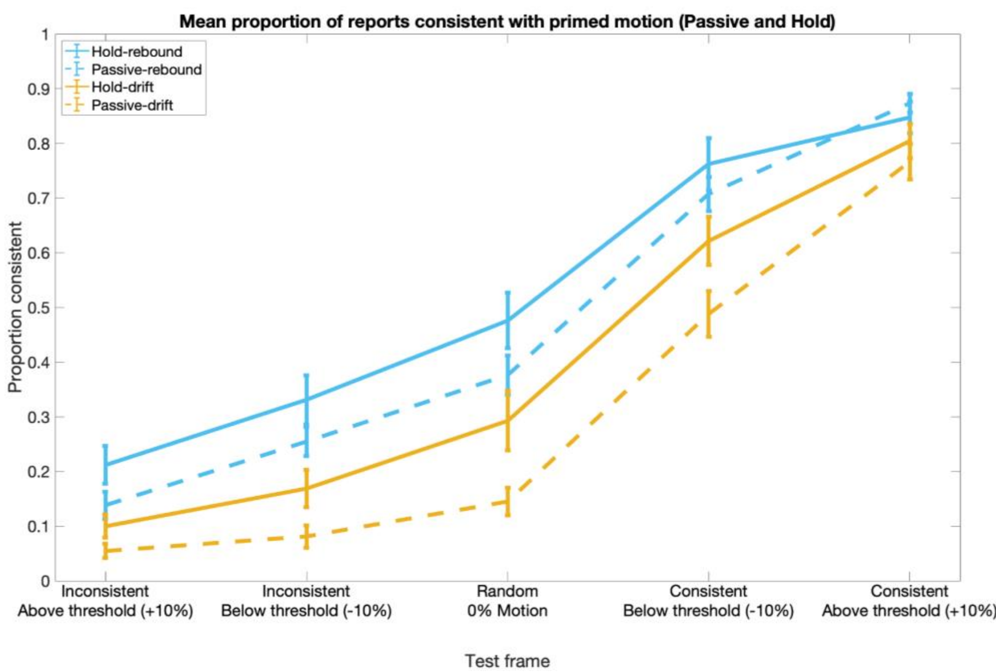

Figure 21. Results for Experiment 4. The mean proportion of prime consistent responses.

To explore whether the strength in subjective control differed for rebounding and drifting, the difference in the mean inflection points for passive and hold was also examined for the two motion types independently. A t-test was performed comparing the mean difference in instruction for rebounding with the mean difference in instruction for drifting. The t-test revealed no difference in inflection point for the two motion types, $t(20) = 1.34$, $p = .196$.

Notably, for both the passive and hold conditions, when participants were presented motion on the test frames below their perceptual threshold, the same proportion of motion is being presented regardless of the direction of the test frames. Yet, interestingly, the slope of the curves revealed in Figure 21 shows an asymmetric relationship between the random condition and the two different types of test frames presented at below threshold (the consistent and inconsistent motion). This asymmetry is associated with the motion nulling effect of presenting participants with inconsistent motion (of the specific type that was used in the methods) in the test frames. To measure the strength of the motion nulling effect, we examined participants' slope for the logistic curve model. The mean slope across conditions was 0.04 ($SE = 0.003$). The slope of participants prime-consistent responses was compared for passive and hold in a t-test. The t-test revealed no significant difference in the slopes of the two instruction conditions. However, a t-test comparing rebound and drifting motion primes did find a significant difference in slopes, with drifting motion having a greater ($M = 0.05$, $SE = 0.004$) slope compared to rebounding motion ($M = 0.03$, $SE = 0.003$), $t(20) = 4.22$, $p < .001$. The difference in slopes for the two motion types suggests that motion nulling was more effective when participants were primed with drifting motion (shifting the slope by 0.02) compared to when they were primed with rebounding motion.

The above ANOVA demonstrated a main effect of instruction, suggesting that participants had increased prime-consistent reports in the hold instruction condition. To assess the strength of subjective control for rebounding and drifting motion types independently, a 2 x 5 ANOVA was conducted, comparing the difference in means from the hold instruction and passive instruction (Figure 22). The analysis revealed a trending effect of there being a greater mean difference for drifting (M_{diff} = 0.09, SE_{diff} = 0.03) compared to rebounding (M_{diff} = 0.06, SE_{diff} = 0.03), $F(1,20) = 4.16$, $p = .055$. There was a main effect of type of test frame, where certain types of test frame had a relatively large mean difference, such as during random trials (M_{diff} = 0.12, SE_{diff} = 0.04), and other motion types had relatively less difference, such as consistent above threshold trials (M_{diff} = 0.006, SE_{diff} = 0.02), $F(4,80) = 4.22$, $p = .004$. There was no interaction between the motion type and type of test frame.

Each of the test frame and motion type conditions were examined independently to assess which conditions participants were able to control the motion. Each of the five test frame conditions for each motion type (10 conditions altogether) were analyzed in a t-test compared to 0 (0 being no difference between the passive and hold). The series of t-tests found that participants were able to control five (or half) of the conditions: (1) rebounding when presented at 0% motion ($p = .017$), (2) drifting when inconsistent and above threshold ($p = .038$), (3) drifting when inconsistent and below threshold (p = .027), (4) drifting when presented with 0% motion (p = .006), and (5) drifting when consistent and below threshold (p = .009; see Figure 22 asterisks).

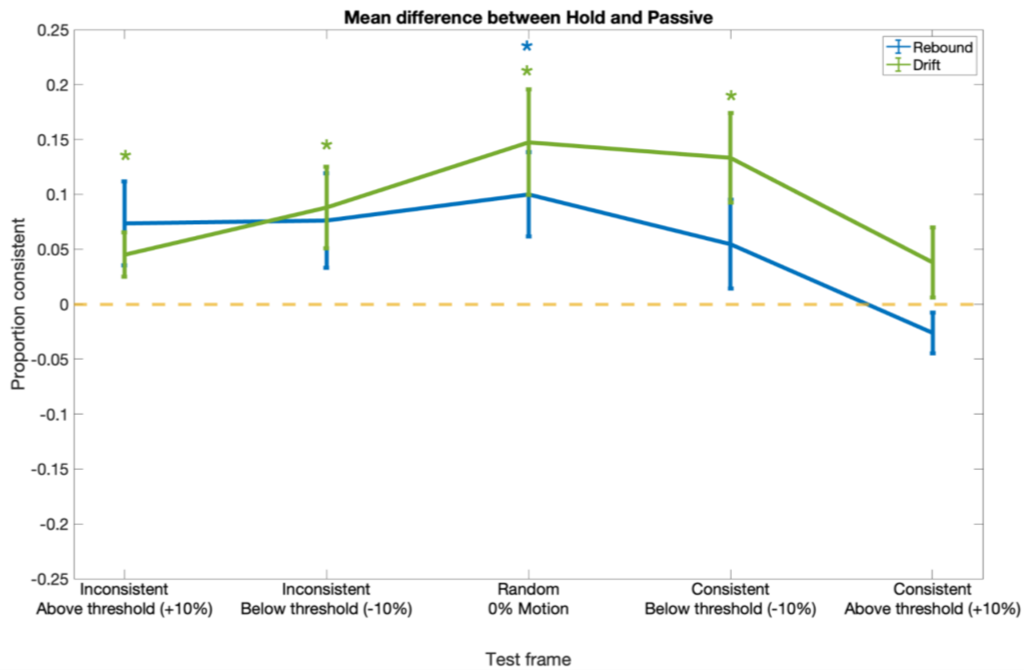

Figure 22. The mean difference between passive and hold prime consistent reports for rebounding and drifting motion primes.

Accuracy performance

Another measure worth examining is the accuracy of participants' reports for the test frames. For the previous measure, mean proportion of prime-consistent responses, this gives us a sense of how participants' perception is impacted by the relationship between motion priming and the motion present in the test frames. However, examining accuracy gives us a general sense of (1) how often participants were aware of the motion presented in the test frames (the inconsistent test frames are especially helpful for assessing this), and (2) whether priming frames contributed to the accuracy of participant reports.

The accuracy of participants' reports were analyzed separately for below threshold conditions and above threshold conditions. A 2-way within subject ANOVA comparing motion type (rebound and drift) and type of test frame (inconsistent, consistent) found a main effect of motion type, where participants were more accurate when reporting rebounding motion ($M = 0.55$, $SE = 0.03$) compared to drifting motion ($M = 0.45$, $SE = 0.04$) present in the test frames, $F(1,20) = 9.70$, $p = .006$. There was also a main effect of the type of test frames where participants were more accurate when reporting consistent ($M = 0.64$, $SE = 0.03$) compared to inconsistent ($M = 0.36$, $SE = 0.03$) motion in the test frames, $F(1,20) = 116.38$, $p < .001$. There was an interaction between the two factors where the rebound bias was observed for consistent, but not inconsistent motion presented in the test frames (Figure 23).

For above threshold motion, a 2-way within subjects ANOVA comparing motion type and type of test frame also found a main effect of motion type, where participants were more accurate when reporting rebounding ($M = 0.76$, $SE = 0.03$) compared to drifting ($M = 0.67$, $SE = 0.03$) motion presented in the test frames, $F(1,20) = 13.38$, $p = .002$. There was also a main effect of type of test frame, where participants were more accurate when reporting the motion presented in consistent (M

= 0.82, *SE* = 0.02) versus inconsistent (*M* = 0.61, *SE* = 0.04) test frames, $F(1,20) = 43.45$, $p < .001$. No interaction was observed between the two factors (Figure 23).

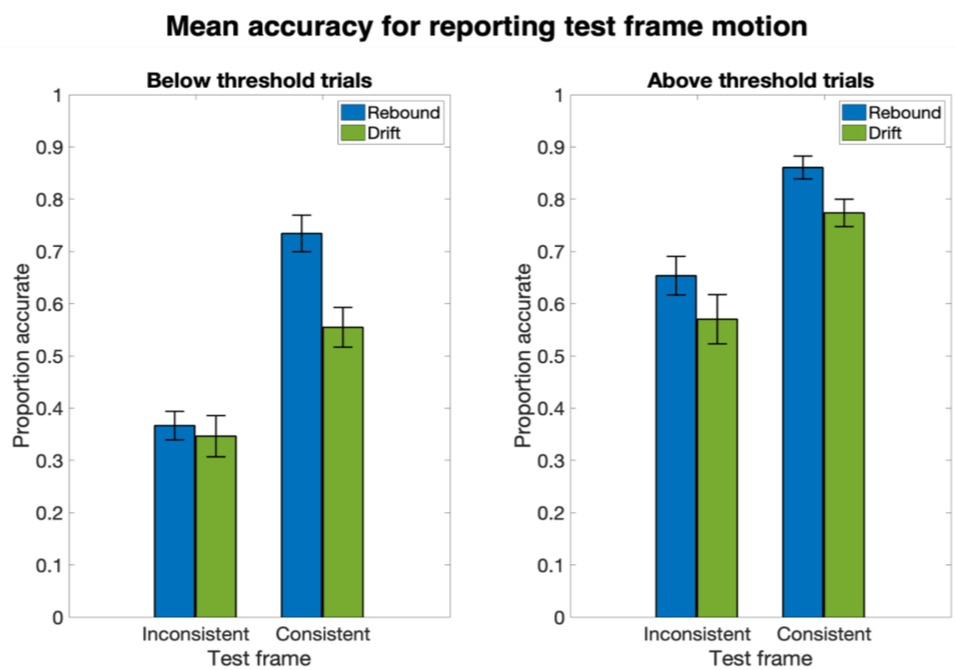

Figure 23. The mean accuracy proportions for reporting the motion presented in the test frames, calculated separately for below threshold test frames and above threshold test frames.

Discussion

The main goal of Experiment 4 was to quantify and compare the influence of higher and lower level factors on the perception of IAM. The main questions this experiment aimed to answer are: (1) Is it possible to quantify the influence of different factors (e.g., subjective control, type of motion prime) on the perception of IAM? (2) If so, to what extent do these factors interact in biasing the perception of IAM?

Overall, Experiment 4 demonstrates that it’s possible to quantify and compare the influence of lower- and higher-level factors on the perception of IAM. We were able to quantify the strength of the rebounding bias under conditions of passive viewing and subjective control. The strength of rebounding motion on participants' proportion of prime-consistent responses was slightly higher in the passive (~33%) compared to the hold (~28%) condition. Overall, this finding matched our prediction that a rebound bias should be observed in the shift of participants’ logistic curves. Initially we predicted that, for 0% motion trials, participants would have around 27% prime-consistent responses when primed with rebounding motion and around 22% prime-consistent responses when primed with drifting motion. However, we found that participants had around 38% prime-consistent responses when primed with rebounding and around 15% prime-consistent responses when primed with drifting motion. One reason Experiment 4 may have observed a more extreme difference between rebound and drift compared to Davidenko et al. (2022; i.e., a higher proportion for rebounding and lower proportion for drifting) is that their study gave participants to report an “other” motion, while this study restricted participants to the four arrows. The different set of report options may have influenced how participants decided to categorize their perceptual experiences.

We were also able to quantify the strength of participants’ subjective control. The results found that under instructions of subjective control, participants required about 15% less prime-consistent motion signal to achieve the same proportion of prime-consistent responses as under passive instructions. This was consistent with our prediction that subjective control would have a lower inflection point compared to passive, suggesting that subjective control can override some of the lower-level factors (e.g., prime-inconsistent motion) that can influence the perception of IAM.

Experiment 4 was able to quantify the effects of motion nulling and facilitation by examining the slopes of participants' logistic curve fits. Notably, as can be observed by the asymmetry in the curves in Figure 21, motion nulling and facilitation was observed for both motion types. However, steeper slopes were observed for drifting compared to rebounding motion, suggesting that motion nulling and facilitations was more effective when participants were primed with drifting motion. This was consistent with our prediction that motion nulling and facilitation would be observed.

Beyond the predictions made for this study, we also explored the difference in mean prime-consistent responses for passive and hold instructions, a measure that gives a sense of the strength of participants' subjective control. A marginally larger difference in passive and hold for drifting instructions was observed, suggesting that when participants were successful at holding the motion, it was more often for drifting priming frames. We followed up on this finding and assessed subjective control for each of the conditions (5 types of test frame) for each of the motion types and found that, overall, participants were successful at holding drifting motion across nearly all of the drifting conditions. This was in contrast to only one rebounding condition that participants were successful at holding: random (0% motion).

One reason participants may have been more successful at holding drifting motion in this context is because the drifting test frames may have been more ambiguous, even when they contained the same level of motion coherence as rebounding test frames. This can be observed in the consistent above threshold differences shown in Figure 22. If a consistent motion signal is being presented with a relatively high motion signal, then we might not expect to observe subjective control (i.e., we'd expect no difference between the conditions since participants are simply reporting what motion is there). However, Figure 22 shows that participants are controlling drifting motion in that context, suggesting that there may be more ambiguity in that context. Additionally, participants tended to need higher levels of motion coherence to detect the presence of drifting motion compared to IAM (and the threshold used for the motion nulling task was a mean threshold). In addition, the results examining participants' accuracy at reporting the motion present in test frames showed that participants were less accurate at identifying the motion presented in drifting test frames. Collectively these factors suggest that the drifting test frames may have been more ambiguous than rebounding frames, and subsequently led to greater subjective control.

Accuracy performance

Another measure that was explored in this study was participants' accuracy when reporting the motion that was actually presented on the test frames. Examining participants' accuracy raised three questions: (1) how often participants were aware of the motion presented in the test frames (the inconsistent test frames are especially helpful for assessing this), and (2) whether priming frames contributed to the accuracy of participant reports.

Participants accuracy performance was examined separately for below threshold and above threshold test frames. Participants were accurate at identifying the motion around 36% of the time when presented with inconsistent below threshold trials and around 64% of the time when presented with inconsistent above threshold trials. Although it’s not clear to what extent the prime-consistent findings are based on conscious or unconscious perception of the motion on the test frames, these accuracy measurements help to give an estimate of how frequently participants may have been consciously aware of the motion presented in the frames.

For below and above threshold test frames, participants were significantly more accurate when reporting the motion present in consistent test frames. This could be at least partially attributed to participants reporting prime-consistent motion on these trials. If consistent motion is facilitating prime consistent reports, then we should also expect increased accuracy for those trials.

The second question concerns whether the type of motion presented priming frames contributed to the accuracy of participants' reports. For below and above threshold trials, participants were more accurate for rebounding trials. We mentioned above that participants may have been able to control drifting motion due to its ambiguity. Here, it’s possible participants were more accurate at reporting the presence of rebounding motion for a similar reason. The threshold task found that participants were able to detect the presence of rebounding motion at lower motion coherence levels compared to drifting, and the thresholds for rebounding and drifting were combined into a mean threshold. It's possible that rebounding motion is less ambiguous for participants. Another possibility is that the rebounding primes (especially consistent and below threshold test frames) contributed more to participants' accuracy than drifting primes. Participants have consistently shown a rebound bias, so it could be that rebounding primes were more effective at priming participants than drifting primes.

Thresholds

Although the motion nulling task was the main task in this experiment, we also measured participants' thresholds for detecting the presence of motion. This was the first IAM study to do so, and this raised its own set of questions: (1) What are participants' thresholds for detecting the presence of rebounding motion in IAM? (2) What are participants' thresholds for detecting the presence of drifting motion in IAM? (3) And, are participants better at detecting the presence of one motion type over the other? The results found that participants tended to detect rebounding motion at around 51% coherence levels, while drifting motion was detected at around 58% motion coherence, and that more participants (n = 10) detected rebounding motion at lower coherence levels (compared to only 4 participants who detected drifting motion at lower coherence levels) compared to drifting motion. Overall, these results suggest that participants were better at detecting the presence of rebounding motion in IAM displays.

Limitations and future directions

The findings presented above should be tempered with additional considerations. First, as mentioned before (see section 'Pilot threshold study'), one of the concerns we had when conducting the pilot study was that participants may be experiencing mixed percepts. The pilot study found that some participants experienced motion types (e.g., diagonal, shear, expansion) that weren't compatible with the report options and one participant experienced mixed percepts. One limitation of the pilot study is that we didn't probe participants on a trial-by-trial basis (in order to avoid verbally suggesting other motion types or mixed percepts). Instead, the pilot study relies on participants reporting at the end of the study that they had these experiences. So, for both the pilot threshold study and Experiment 4 one challenge is that it's not clear how frequently participants are experiencing motion patterns that aren't reportable with the arrow options available.

Another consideration is that this experiment only used two priming frames. Past IAM studies have used a variety of configurations: several frames of priming in a persistence task (Allen et al., 2022; Davidenko et al., 2017), continuous viewing and report (Allen et al., 2022), and a few priming frames with a few test frames (Davidenko & Heller, 2018; Davidenko et al., 2022; Heller & Davidenko, 2018). In the context of the motion nulling task presented here, participants are presented with only two priming and two test frames. This makes it unclear to what extent the findings here would generalize to other IAM task configurations, including ones with more priming frames and opportunities for participants to report their perception of IAM over a longer span of time. Future studies could explore whether the pattern of results obtained here were specific to the task or whether they can generalize to other configurations for presenting and reporting IAM.

Finally, subjective control in other polystable phenomena studies (and in Experiments 1 and 2) may also involve the instruction for participants to 'change' their interpretation of the stimulus. For this experiment we opted to only instruct participants to 'hold' their perception of the stimulus. However, there are reasons to think that 'change' and 'hold' may not be comparable ways of controlling the motion, as they may require the participant to control the motion in different ways. As such, future research could explore the strength of 'changing' the motion for participants and see how this compares with the strength of 'holding' perceptions of IAM.

Conclusion

Experiment 4 used a motion nulling procedure to explore the influence of low and high factors on participants' perception of IAM. Participants were primed with two frames of motion followed by two test frames. The test frames manipulated the motion coherence level and motion type. Participants reported the direction of motion that they perceived on the final two frames. With our results, we were able to quantify a number of factors, including: the strength of the rebound bias, subjective control, motion nulling, and motion facilitation. Experiment 4 provides a better understanding of the extent to which these different factors may interact with each other and affect participants' perception of IAM.

Chapter V

General discussion

The four experiments presented here lay the initial groundwork for researching subjective control of IAM. First, Experiments 1 and 2 explored whether subjective control of polystable stimuli extends to IAM, a new, maximally ambiguous motion stimulus. Experiment 1 was the first IAM study to demonstrate that participants can perceptually control their IAM in a motion priming task. The motion priming task was based on the methods used in the first IAM study conducted by Davidenko et al. (2017), and assisted participants with the perception of an initial motion pattern (motion primes) and used a relatively simple report method where participants reported only one perceptual change, if it occurred, during the trial. Experiment 2 explores a similar question as Experiment 1 but sought to bring the methods more in line with other studies examining subjective control of polystable stimuli by removing the motion priming. For this task, participants were not assisted with motion primes and instead required them to self-generate initial motion patterns. Additionally, participants reported their percepts dynamically across the 10 s trials. Together, the results of Experiments 1 and 2 demonstrate that, similar to other polystable phenomena, participants can subjectively control their perceptions of IAM.

Experiment 3 explored IAM as a maximally ambiguous stimulus with potentially countless interpretations and extended previous IAM research by testing whether participants could perceive and subjectively control motion patterns beyond translation and rotation. Experiment 3 tested 14 different motion types, half of which contained motion types not yet explored in IAM (expansion, contraction, and shearing). Experiment 3 found that observers were able to perceive many and control a few interpretations of IAM, supporting previous assumptions that observers likely experience more interpretations of IAM than other polystable phenomena.

The main goal of Experiment 4 was to explore the influence of low and high factors on participants' perception of IAM. To test this, participants were presented with two priming frames, followed by two test frames. The test frames were manipulated to present participants with (1) a nulling (prime-inconsistent) motion below and above their perceptual threshold, (2) with a facilitating (prime-consistent) motion below and above their perceptual threshold, and (3) with 0% motion. After each trial, participants reported the direction of motion that they perceived on the final two frames. With our results, we were able to quantify a number of factors, including: the strength of the rebound bias, subjective control, motion nulling, and motion facilitation.

Collectively, Experiments 1 - 4 help us to understand IAM as a new stimulus. One of the most robust features of IAM is the 'rebound bias.' As mentioned before, the rebound bias reflects participants' tendency to see rebounding (e.g., up-down-up-down) motion patterns compared to other (i.e., drifting) motion types. One of the benefits of Experiments 1, 3, and 4 is that they all expand previous research on the rebound bias. Experiments 1 found that the rebound bias interacted with participants' ability to subjectively control the motion. In particular, the rebound bias appeared to facilitate subjective control. Experiment 3 found that participants had longer total durations for rebounding motion types and tended to report rebounding motion types as clearer. Experiment 4 was able to quantify the strength of the rebound bias. Strikingly, the rebound bias was around twice as strong as subjective control. Past research suggests that rebounding may be a ‘default’ percept (Heller & Davidenko, 2018; Hseih, Caplovitz, & Tse, 2005). The findings from Experiments 1,3, and 4 are consistent with this notion.

One of the most important factors explored in Experiment 1 - 4 was subjective control of IAM. Subjective control, as mentioned before, occurs when observers intentionally bias their perception of polystable phenomena. Subjective control has been demonstrated widely, across a variety of polystable phenomena. Yet, subjective control of IAM raised a number of questions due to IAMs unique features. IAM affords countless possible interpretations and at times requires participants to self-generate their initial interpretations. These unique features raised questions about whether subjective control would be possible in IAM. Experiments 1 and 2 were the first studies to demonstrate participants' ability to control their perceptions of IAM. Experiment 3 was the first study to demonstrate that across a set of 14 tested motion types, participants were able to only control a couple of previously tested motion types (translation and rotation) and struggled to control some newly tested motion types (expansion, contraction, shear). Finally, Experiment 4 was the first study to quantify subjective control of IAM. Importantly, Experiments 1 - 4 showed subjective control across different IAM configurations, suggesting that observers can control their perception of IAM in a variety of contexts. Collectively Experiments 1 - 4 lay some groundwork for understanding how subjective control works in IAM. The results presented here suggest that observers can control their perception of IAM across a variety of task configurations and motion types and quantifies the strength of subjective control.

Limitations and future directions

Individual differences were presented for Experiments 1 - 3, and the findings raise questions worthy of exploration in the future. Experiments 1 showed a fair amount of variation in individuals' change and hold persistence (Figure 8A), and Experiment 2 showed a spread in participants' change and hold durations (Figure 8B). Experiment 3 observed a number of individual differences. First, differences were observed across participants' total durations for perceiving each of the 14 motion types (Figure 12). Notably, some participants seemed to have an overall ability to perceive IAM across the 14 motion types (these are the participants near the bottom of the heatmap with darker blue cells), while other participants struggled to experience any of the 14 motion types (these are the participants near the top of the heatmap with lighter cells). There were also differences for how many interpretations of IAM each participant could experience. Figure 14 shows a wide spread across the 14 motion types. Finally, Individual differences were also observed in total durations for passive compared to hold (Figure 16). Similar to the passive condition, some participants seemed to show an overall ability to control the motion while others did not. Notably, there was more individual variation for the passive condition compared to the subjective control condition for Experiment 3.

Similar individual differences have been observed across a variety of IAM studies, and some of the questions raised in the general discussion of Experiments 1 and 2 apply here. Do we observe these individual differences due 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. Future research could explore what factors contribute to individual differences and why they arise.

A limitation of these Experiments 1 - 4 is determining whether the pattern of results that we obtained were due to changes in participants' perceptions or their response behaviors. For example, it could be that when participants are instructed to 'hold', their decision criteria for reporting particular motion patterns is influenced rather than their ability to mentally control the motion. (Importantly, this isn't only a problem for these studies, but for any similar tasks.) Participants may be more or less flexible about categorizing certain motion directions or levels of coherence as a certain motion pattern in IAM, reflecting individual differences in decision criteria for reporting whether a particular motion pattern is being perceived. It's possible that in these studies some combination of participants' perceptions and decision criteria are being modified by our instructions. Importantly, robust rebounding biases were observed in Experiments 1, 3 and 4 suggesting that participants' reports weren't just based on experimental demand. However, future research could help parse the role of decision making in the perceptual reports for IAM.

Conclusion

The maximally ambiguous nature of IAM makes it a great candidate for studying the constructive nature of perception. The studies presented here give a glimpse into how subjective control of IAM can bias how perceptions of IAM are constructed, and subjective control is just one way that IAM perception can be influenced. Many additional low level (e.g., velocity, geometry, density) and high-level factors (e.g., knowledge, learning, attention) already mentioned in this paper will affect how IAM is perceived. Future research in IAM has much space to expand, exploring how perception can be constructed in such a unique and rich stimulus.

Appendix A

Experiment 2 survey

List of strategy survey questions:

1. *"When you were instructed to CHANGE or HOLD the motion, did you happen to use any strategies*?"

Response options: Yes or No

If the participant answered yes to question 1, then they were instructed to answer questions 2-5. If they answered no, they were instructed to skip to questions 6-7.

2. *"When you were instructed to HOLD the motion, what strategy/strategies did you use? Please briefly describe."*

   Response type: Short answer

3. *"When you were instructed to CHANGE the motion, what strategy/strategies did you use? Please briefly describe."*

   Response type: Short answer

4. *"If you used multiple strategies, did certain strategies appear to be more effective?"*

   Response type: Short answer

5. *"Did it seem easier to CHANGE or HOLD the motion? Please briefly describe."*

Response type: Short answer

6. "If you didn't use any strategies, please briefly describe your experience during trials when you were instructed to CHANGE the motion."

Response type: Short answer

7. "If you didn't use any strategies, please briefly describe your experience during trials when you were instructed to HOLD the motion."

Response type: Short answer

Participants were instructed to respond to all of the remaining questions.

8. "How successful were you in maintaining focus on the red fixation dot throughout the experiment?"

Response type: Short answer

9. "Did you notice yourself intentionally or unintentionally using eye movements in order to CHANGE or HOLD the motion?"

Response options: Yes, intentionally; Yes, unintentionally; Yes, both intentionally and unintentionally; No

10. "If so, briefly describe what you noticed about your eye movements?"

Response type: Short answer

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