Using Visual Illusions to Examine Action-Related Perceptual Changes

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ABSTRACT

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Action has many influences on how and what we perceive. One robust example of the relationship between action and subsequent perception, which has recently received great attention in the cognitive sciences, is the "intentional binding" effect: When people estimate the timing of their actions and those actions' effects, they judge the actions and effects as having occurred closer together in time than two events that do not involve voluntary action (Haggard, Clark, & Kalogeras, 2002). This dissertation examines the possible mechanisms and consequences of the intentional binding effect. First, in Chapter 1, I discuss previous literature on the relationships between experiences of time, action, and causality. Impressions of time and causality are psychologically related: The perceived timing of events impacts, and is impacted by, perceived causality. Similarly, one's experience of causing and controlling events with voluntary action, sometimes called the *sense of agency*, shapes and is shaped by how those events' timing is perceived—as shown by the intentional binding effect.

In Chapter 2 I present a series of experiments investigating a hypothesized mechanism underlying the intentional binding effect: Actions may lead to a slowing of subjective time, which would explain the intentional binding effect by postulating a shorter experienced duration between action and effect. This hypothesis predicts that, following action, durations separating any two stimuli would appear subjectively shorter. We tested this hypothesis in the context of visual motion illusions: Two visual stimuli are presented in short succession and if the duration between the stimuli (inter-stimulus interval; ISI) is short, participants tend to perceive motion such that the first

stimulus appears to move to the position of the second stimulus. If actions shorten subjective durations, even in visual perception, people should observe motion at longer ISIs when the stimuli follow voluntary action because the two stimuli would be separated by less subjective time. Three experiments confirmed this prediction. An additional experiment showed that verbal estimates of the ISI are also shorter following action. A control experiment suggested that a shift in the ability to prepare for the stimuli, afforded by the participant initiating the stimuli, is an unlikely alternative explanation of the observed results. In Chapter 3 I further investigate whether temporal contiguity of actions and their effects, which is known to impact intentional binding, affects perceptions of visual motion illusions. Two experiments showed that temporal contiguity modulates perceptions of illusory motion in a manner similar to contiguity's effect on intentional binding.

Together, these results show that actions impact perception of visual motion illusions and suggest that general slowing of subjective time is a plausible mechanism underlying the intentional binding effect.

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Acknowledgments

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Dedication

Hoiran, this is for you.

Introduction[1]

Abstract

The experience of controlling events in the external world through voluntary action—the sense of agency (SoA)—is a subtle but pervasive feature of human mental life and a constituent part of the sense of self (Gallagher, 2000). However, instead of reflecting an actual connection between conscious thoughts and subsequent outcomes, SoA may be an illusion (Wegner, 2002). Whether this experience is an illusion, indicating no actual causal connection between conscious intention and physical outcome in the world, has been the focus of intense philosophical and scientific debate since the beginnings of these fields of inquiry (e.g. Kane, 2011). More recently, the fields of experimental psychology and cognitive neuroscience have begun to identify specific antecedents of the experience of agency—whether veridical or not (Haggard, 2008). Similar to the perception of causality, which depends on the temporal structure of the events (Michotte, 1963), humans' experience of their agency is very sensitive to the temporal interval separating bodily actions from the external effects of those actions (Metcalfe, Eich, & Castel, 2010). Accordingly, just as studies on perception of causality in the outside world have paid much attention to the temporal configuration of events (Michotte, 1963; Scholl & Tremoulet, 2000), many contemporary studies have also focused on the contribution of the temporal organization of events giving rise to SoA, and in turn how experienced agency might influence subjective time (Haggard et al., 2002; Moore & Obhi, 2012). Here, I review existing evidence suggesting that subjective time both influences and is influenced by perceived causality in general, and experienced agency in particular. Finally,

[1] Parts of this chapter have been previously published in Vuorre, M. (2017). On Time, Causation, and the Sense of Agency. *Journal of Consciousness Studies*, *24*(3–4), 203–215.

I briefly speculate that these findings may support predictive coding theories of cognition and perception (e.g. Hohwy, 2013).

Introduction

In early experimental studies on the perception of causality, Michotte (1963) identified the temporal relationship between two objects' motion as the most important determinant of the perception of cause and effect: In a series of experiments participants saw two disks, one of which moved to touch the other disk which subsequently 'launched' to movement as if propelled by the first object's touch. The key finding was that this 'launching effect'—perceptually experiencing that object A 'launched' object B into movement—depended on a specific temporal relationship between the two disks' movement. If the second disk begun moving before being touched by the first disk, people simply perceived two independently moving disks. Similarly, if the second disk did not move until much later after it was touched by the first disk, people also perceived two independently moving disks. However, when the temporal delay between the first disk touching the second and the second disk's movement onset was just right—depending on the specific configuration of the objects, usually under about a fifth of a second (Michotte, 1963, p. 22)—people unequivocally perceived that the first disk caused the second one's movement: With short time intervals, the two disks' motions were seen as causally connected[2].

Later experiments investigating judgments of causality in similar perceptual tasks have found that when outcomes follow participants' actions probabilistically (e.g. actions produce outcomes on 75% of trials), increasing the delay from actions to their effects reduces judgments of the actions' causal power over the effects independently of the probabilistic contingency (i.e. the probability that an event follows an action; Shanks, Pearson, & Dickinson, 1989). Therefore,

[2] In some variations of the basic 'Michotte display', completely removing the temporal delay between the disks' movement can also result in the perception of a single unitary object moving through the display, even if these objects are colored differently (Michotte, 1963, p. 45), reminiscent of visual illusions of apparent motion (Kolers & von Grünau, 1976; Wertheimer, 1912).

time seems crucial for inferences about causality, even in the presence of uncertainty. It is important to note that while other factors, such as prior beliefs, can influence when and where causality is perceived, under suitable conditions the perception is very quick to occur—little or no conscious deliberation is required—but not automatic in the sense that people would have some underlying direct access to information about physical causality. Instead, causality is quickly inferred from the statistical regularities and temporal features of the observed events (Hume, 1748; Lagnado & Sloman, 2006). That is, objects and events must be temporally combined and structured in specific configurations for people to perceive causality: "any adequate theory of causality judgement […] must account for effects of both contingency and [temporal] contiguity" (Shanks et al., 1989, p. 143).

However, the relationship between time and causality is not restricted to actual temporal properties of events informing perceptions of causality. Perceived or judged causality between two events can also influence the subjective temporal properties of those events. For example, human participants anticipate that events occur earlier in time when they have learned that the events are caused by a mechanical agent, even at very short time scales (under 1.5 seconds between the two events; Buehner, 2012). Further, the effect of beliefs about causality on time perception is not limited to magnitude judgments, such as numerically estimated inter-event intervals; perceived causality between two events can shift the perceived temporal order of observed events (Bechlivanidis & Lagnado, 2016). In this study, participants observed modified 'Michotte displays', whose objective temporal order sometimes violated principles of causality (an object started moving before another object touched it.) In these cases, participants sometimes ignored the objective temporal structure of the events and instead reported seeing events in the temporal order implied by the assumed causal structure. Perceived causality can also influence subjective estimates of event timing on a much longer time scale than the two studies highlighted above. In studies on historical events, Faro and colleagues have found that when people believe that two historical events are causally related, they estimate that these events occurred closer together in time than two events that they don't believe are causally connected (Faro, Leclerc, & Hastie, 2005; Faro, McGill, & Hastie, 2013).

These studies suggest that the flow of information between time and perceived causality (of external events) is bidirectional. Perceived causality can inform judgments and perceptions of the temporal relationship between events, and the actual temporal distance between events can strongly modulate perceived causality. But does the bidirectional relationship also hold for time and people's perceptions about the causal powers of their own actions? Could such intimate self-knowledge be modulated by what happens when in the outside world, and could an individual's sense of agency (SoA) influence how time is perceived? If SoA is anything like inferences about causality in general, it is possible that SoA is also modulated by objective temporal properties of events, and that subjective time can be modulated by SoA.

Time influences experienced agency

Although some early theories of how humans come to regard themselves as conscious causal agents took the view that people knew directly that one is an agent with causal powers (de Biran, 1942; see also Michotte, 1963, p. 11), more recent theories suggest that the sense of agency is inferred from the temporal, spatial and psychological structure of intentions, actions, outcomes, and other related events. For example, according to the theory of apparent mental causation (Wegner, 2002; Wegner & Wheatley, 1999), the experience of causing actions by intending them is an illusion constructed retrospectively by the brain when three requirements are satisfied: The intention must occur before the action, and the intention and action must be compatible and causally exclusive—i.e. the thought should be the only possible cause for the action. This theory implies that the sense of agency is a post-hoc construction formed only after the outcomes of the actions are known. However, more recent evidence suggests that SoA is modulated by factors necessarily operating before the outcomes are known to the agent (Chambon, Sidarus, & Haggard, 2014; Sidarus, Chambon, & Haggard, 2013; Sidarus & Haggard, 2016; Sidarus, Vuorre, & Haggard, 2017a, 2017b; Sidarus, Vuorre, Metcalfe, & Haggard, 2017). Although apparent mental causation is therefore not a comprehensive model of the sense of agency, it highlights a common feature of many models of the sense of agency, namely that the experience of agency is not automatically known by the agent, but rather is influenced by many factors, including the temporal properties of events.

Apparent mental causation has received little empirical verification (but see e.g. Wegner, Sparrow, & Winerman, 2004), possibly because the specific nature of subjective intentions has been difficult to determine and measure empirically. It nevertheless provides a useful analogy between the perception of causality in the external world, and the perception—or construction—of the sense of agency. Just as Michotte's experiments showed that external causality is perceived when the temporal properties of events are just right, SoA is also sensitive to the specific temporal configuration of events: In three experiments using an arcade-style computer game, players reported feeling substantially lower SoA when a temporal interval (either 1/4 or 1/2 second) was introduced between the player's mouse movement and the game cursor's movement (Metcalfe et al., 2010). Further supporting the claim that sensitivity to this temporal interval is crucial for the sense of agency, individuals with schizophrenia—a disorder whose one core deficit relates to difficulties distinguishing self- and other-caused events—are not affected by a temporal lag between actions and outcomes in the same computer game (Metcalfe, Snellenberg, DeRosse, Balsam, & Malhotra, 2012). These studies, and others investigating how different manipulations in computer games influence the sense of agency (Metcalfe & Greene, 2007; Vuorre & Metcalfe, 2016), support the general idea that the sense of agency is not directly perceived but rather inferred from multiple sources and cues (Synofzik, Vosgerau, & Lindner, 2009). Specifically, the sense of agency—the subjective experience of causing and being in control of actions and their effects—is decreased by longer intervals separating one's voluntary action, and their subsequent effect.

Voluntary actions influence subjective time

Similar to perceptions of causality between external events, the human sense of agency is influenced by temporal properties of events, such that the sense of agency is strongest when actions precede their effects with no or very short delays (Metcalfe et al., 2010). However, evidence also shows that voluntary actions, and the ensuing sense of agency, can influence subjective time. Before reviewing this evidence, I briefly introduce one influential approach for measuring subjective timing of intentions, actions, and effects.

Chronometry of voluntary action

In a seminal set of experiments, Benjamin Libet and colleagues asked volunteer participants to observe a clock face with one rapidly rotating hand (one rotation about every three seconds), and to make simple hand movements whenever they wanted to (Libet, Gleason, Wright, & Pearl, 1983). After each hand movement, the participant reported the onset of the feeling of wanting to move (W judgment) and when they thought they had actually moved the hand (M judgment) by reporting the recalled position of the clock hand at the time of the event. These judgments constituted the subjective chronometric evaluations of events, which could in turn be compared to objective timings of the events. While the participants were performing the task, the electrical activity of their brains was recorded with an electroencephalogram (EEG), and the muscular activity at the hand was recorded with an electromyogram (EMG). As a result, Libet et al. were able to compare the time course of the brain's electrical activity (EEG) with the participant's judgment of when they first wanted to move (W), and also the objective timing of the actual hand movement (EMG) to the subjective judgment of when the participants thought they had moved (M). The key finding was that the W judgments were reliably preceded by a slow ramping up of brain activity detected with the EEG (the readiness potential; Kornhuber & Deecke, 1965), from which the authors concluded that the intention to produce voluntary actions, and therefore the decision to move, is determined by unconscious brain processes before the person is aware of wanting to move. This interpretation of the results was fiercely critiqued (e.g. see commentary in Libet, 1985), and recent computational models suggest that the readiness potential reflects random neuronal noise instead of a unitary unconscious mechanism determining when to act (Schurger, Mylopoulos, & Rosenthal, 2015; Schurger, Sitt, & Dehaene, 2012). The second finding from the initial study was that participants' judgments about when they had moved their hand (M judgment) reliably preceded the hand movements by about 80 milliseconds. Most importantly for the present discussion, however, the study provided an innovative (but controversial; see commentary in Libet, 1985) method for assessing the subjective timing of events, and relating those subjective chronometric judgments to the events' objective temporal properties.

Intentional binding

Libet's clock task was later adopted to studying the time course of action awareness in more detail, and how agency might influence the perceived timing of actions and effects: Instead of only asking about the subjective timing of intentions and actions, Haggard and colleagues (Haggard et al., 2002) asked if operant (effect-causing) voluntary actions can modulate the subjective timing of events in the intention-action-effect chain of events. They modified the Libet task to include, on some trials, events caused by the action (a short beep following the action by 250 milliseconds), and on some trials replaced the voluntary hand movements with involuntary hand movements caused by transcranial magnetic stimulation (TMS) pulses to the participant's parietal cortex. With this design, whereby on some trials the hand movement (either voluntary or involuntary) caused an effect (auditory beep), and on other trials these events occurred in isolation, Haggard et al. (2002) investigated if one possible mechanism by which the brain produces an experience of controlling external events—the sense of agency—relates to subjective temporal binding of voluntary actions and their effects. Indeed, they discovered that operant voluntary hand movements—ones that were followed by a beep—became temporally bound to their apparent effects. That is, on trials where a voluntary action caused a beep, the judgments of when the action occurred were shifted forward in time toward the beep, and judgments of when the beep occurred were shifted backward in time, toward the action that caused it. For involuntary operant trials, where the TMS-produced hand movements were followed by tones, they instead found temporal repulsion, whereby the judgments moved further away from each other in subjective time, in comparison to baseline (action-only or effect-only) trials. From these results, the authors suggested that "the brain contains a specific cognitive module that binds intentional actions to their effects to construct a coherent conscious experience of our own agency." (Haggard et al., 2002, p. 385).

The observed temporal binding of intentional actions and their sensory consequences was dubbed 'intentional binding', because the binding effect was restricted to voluntary effect-causing movements, and because similar involuntary movements resulted instead in temporal repulsion of the judged timing of action and effect (Haggard et al., 2002). Although the relationship between explicit judgments of agency and intentional binding is still somewhat unclear, as some studies have found that they are only weakly if at all correlated (Dewey & Knoblich, 2014; one suggestion is that they somewhat independently measure explicit and implicit aspects of the sense of agency, respectively, Moore, Middleton, Haggard, & Fletcher, 2012), this modulation of time perception has been used in a large number of studies yielding valuable insight into the nature of SoA and temporal awareness of actions and their outcomes (Moore & Obhi, 2012)[3].

Although a great number of studies have examined various influences on intentional binding, the underlying mechanism of this modulation of subjective time has received less attention (Moore & Obhi, 2012). One study used judgments of simultaneity of electric shocks following voluntary and involuntary action to examine if modulation of an internal clock might account for intentional binding (Wenke & Haggard, 2009). According to internal clock models of time perception, judgments of interval durations result from readouts of the number of 'ticks' generated by an internal clock during a given interval (Gibbon, Church, & Meck, 1984). Modulations to interval judgments can then be explained in terms of changes to the tick-rate of the clock, or how these ticks are recalled from memory (Wearden, 2008).

Wenke and Haggard (2009) hypothesized that voluntary actions and their effects seem closer in time because voluntary actions slow an internal clock, and therefore lead the two events to be separated by fewer ticks. If this was the case, then two events presented during the action-effect interval would be separated by fewer ticks following voluntary actions. In the experiment, participants produced a tone with either a voluntary key-press, or an involuntary key-press (the finger on the key was depressed by a machine). During the key-press – tone interval, they received two closely placed electric shocks on the hand that pressed the key, and following the tone, judged whether the two shocks were simultaneous or not. In support of the slowed-clock hypothesis,

[3] Recent evidence has also called into question whether intentional binding is restricted to voluntary actions, or if it instead reflects a more general effect of perceived causality on timing judgments (Buehner, 2012).

participants required more time between the two shocks in the voluntary action condition, in contrast to the passive movement condition, to be able to correctly judge them as not simultaneous. These results were interpreted as suggesting that the electric shocks were separated by fewer ticks in the voluntary action condition, making the temporal discrimination more difficult. These results therefore suggest that intentional binding results from a temporarily slowed internal clock, which in turn allows actions and their effects to be separated by fewer ticks of the internal clock, making them appear as closer together in time.

In line with these results, another study found that voluntary actions change visual perception of illusory motion in a manner that would be expected by an online subjective shortening of intervals following action (Vuorre & Metcalfe, 2017). In this experiment, participants observed two static frames of visual stimuli that could result in specific visual illusions of motion if the frames were separated by a short interval (Ternus illusion and apparent motion; Ternus, 1926; Wertheimer, 1912). The participants either passively observed the displays or observed them following a voluntary hand movement. Results showed that participants perceived the illusions at longer inter-frame intervals when the stimuli followed voluntary actions, suggesting that voluntary actions cause a temporal rate shift, not only in the tactile domain in a bodily location near the movement, as suggested by Wenke and Haggard (2009), but also in global temporal awareness, and reinforce the hypothesis that intentional binding might reflect a temporary slowing down of an internal clock. More generally, these findings are consistent with the theme of the current paper: Experienced causality and agency can modulate estimates of temporal intervals, judgments of when events occur, and even perceptual phenomena that are dependent on the subjective flow of time, such as tactile temporal simultaneity judgments and visual illusions of motion.

Role of prediction

A common theme above has been that perceptions of causality, agency and time are to a degree inferential, in the sense that these perceptions are sometimes influenced by information that is not indicative of the objective passage of time, degree of agency or causality. An illustration of the inferential nature of time perception, for example, is the intentional binding effect, whereby one's voluntary actions change how time is perceived, although information about one's actions—and their effects—is not really about time. Note that by 'inference' here I do not mean conscious deliberation, but rather something akin to unconscious integration of multiple sources of information, some of which are not objectively informative of the to-be-judged quantity. It is also only in this weak sense that SoA can be considered an illusion: SoA is influenced by information that doesn't necessarily pertain to the objective degree of agency, so one may sometimes experience SoA in the absence of actual agency, because some of these potentially non-veridical sources of information lead one to believe so (e.g. Wegner et al., 2004).

Therefore, it may be that the perception of causality is an inference, in the sense described above, mostly based on learned associations between co-occurring events (Hume, 1748; Michotte, 1963), or that the sense of agency is inferred from various cues available to the agent (Synofzik et al., 2009). In either case, evidence suggests that the relationship between experiences of time and agency is bidirectional; that is, experienced causality and agency are informed by time, and perceptions of time are informed by experienced causality and agency. Although a mechanistic understanding of these effects is still lacking, they are suggestive of unifying theories of cognition and perception whereby prior top-down expectations shape the stream of experience—the so-called 'predictive coding' and 'Bayesian brain' hypotheses (Clark, 2013; Friston, 2010; Hohwy, 2013).

An early explanation of the intentional binding phenomenon suggested that it might reflect an approximation of Bayesian inference in the presence of uncertainty about event timing (Eagleman & Holcombe, 2002). Under this Bayesian framework, because individuals have learned through experience that causally connected events tend to happen close together in time, and that their actions are likely to cause outcomes in the world, individuals can—on average—improve the estimated timing of events by combining these prior expectations with noisy incoming sense data. In other words, when asked to estimate the timing of an action and its sensory consequent, people would tend to judge that these two events occurred closer together than two passively observed events, because of the prior assumption that their actions are likely to cause outcomes, and that causes and effects are likely to occur close together in time. In this framework, the subjective experience of event timing and agency is a combination of the current stream of incoming sensory information and top-down expectations. This framework may be adopted to explain the intentional binding effect (Eagleman & Holcombe, 2002), but importantly can also be reversed to explain the bidirectional influence between perceived time, causality and agency, as explored above. In the case of judgments of agency, for example, in ambiguous situations as to whether 'I' caused some outcome in the environment, the temporal proximity of my action to an event in the world may be used to erroneously infer that 'I' did it, even when in fact the action and a sensory event are not actually causally related (Wegner & Wheatley, 1999). Similarly, when people have little information about actual causal relations between external events, they use information about temporal co-variation to guide their estimates of causality (Lagnado & Sloman, 2006).

Generally, the notion of combining prior information with noisy sensory inputs is in accordance with theories of cognition and perception as probabilistic, predictive inference (Clark, 2013; Friston, 2010; Hohwy, 2013). According to these theories, cognition and perception arise from unconscious inference about the possible external causes of sensory inputs using Bayes' rule. This inference requires an internal model in the form of a probability density, which assigns prior probabilities to hypotheses. These probabilities are then updated in light of incoming sense data to yield posterior probabilities of hypotheses, which then dictate the resulting perceptual experience (for a clear extended discussion of this idea, see Clark, 2015, p. 39-41). One suggestion then, generalizing from the intentional binding example above, is that the bidirectional relationship between perceptions of time and causality (or agency) results from a prior positive correlation, in people's internal models, between two events occurring close together in time and them being causally related. That is, one would, all other things being equal, expect that these properties are more likely to occur together. The prior correlations would parsimoniously translate to directional influences, the direction depending on whether one is trying to guess the time interval between two events, or whether the two events are causally related.

Although much of the empirical data reviewed here are broadly in line with the idea that perceptions of time can inform and be informed by perceptions of causality and agency, future research should attempt to move toward formal modeling of how such information exchange occurs. An intriguing avenue for future research in this field would be to investigate whether predictive coding theories could, in fact, explain the relationship between time perception, sense of agency, and perceptions of causality.

Conclusion

Experiences of causality, agency and time are nearly omnipresent in human cognition: Rarely a moment goes by without us noticing that a moment has passed, and that one event during that moment caused another event in a future moment. Accordingly, we can also rapidly evaluate whether 'I' was the cause of some or other event in a continuous stream of events. This chapter has reviewed evidence suggesting that subjective time and (self-) causality are connected in a bidirectional manner: When the situation calls for it, humans can use information from one domain (e.g. time) to inform judgments in another domain (e.g. agency). Evidence suggests that this two-way connection between time and causality is a primitive one, that its use does not require conscious deliberation, and that information from one domain can influence conscious experience in another domain. The evidence reviewed here led to speculations that the relationship between time and (self-) causality might be explained by principles of predictive coding theories of cognition and perception: In the presence of uncertainty, the brain uses the learned correlation between a short time interval separating two events, and their seeming causal connectedness to inform judgments in either domain.

Voluntary Action Alters the Perception of Visual Illusions[4]

Abstract

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

[4] Parts of this chapter have previously been published in Vuorre, M., & Metcalfe, J. (2017). Voluntary action alters the perception of visual illusions. *Attention, Perception, & Psychophysics*, *79*(5), 1495–1505.

Introduction

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

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

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

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

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

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

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

Experiment 1

Method

Participants

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

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

Apparent motion task

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

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

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

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

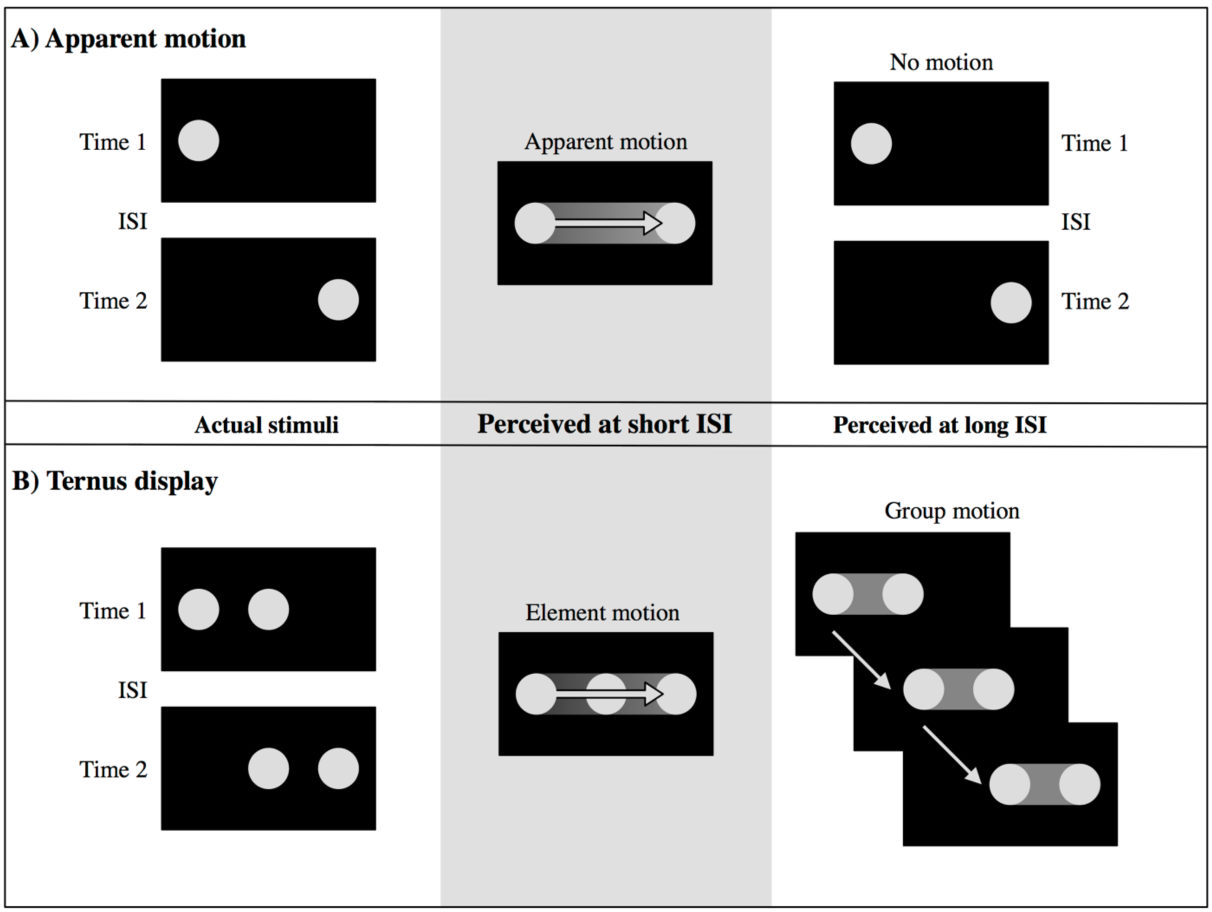

Figure 2.1. Motion illusion displays used in the Experiments.

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

Interval estimation task

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

Results and Discussion

Apparent motion

While we chose the range of ISIs to capture the ISIs over which most participants see apparent motion as sharply declining function of ISI (Kolers & Pomerantz, 1971) there is variability in this percept (Ekroll, Faul, & Golz, 2008). For our purposes, there would be no possibility of measuring a difference between conditions if a participant failed to show any sensitivity to ISI in the range of ISIs investigated. We therefore rejected participants who did not show at least a 10% decline in apparent motion responses from the shortest ISI to the longest, averaged over both conditions. We chose this exclusion criterion because a change in percentage seemed more appropriate as a model-free rule for rejection, in contrast to a rule that would have first required us to fit models to the participants' data. It also offered a good balance between too strict (rejecting participants who were somewhat sensitive to changes in ISI) and too lenient (including participants who were not at all sensitive to ISI). This rule excluded four participants and left a final sample size of 20 participants. Additionally, one participant quit the study before the second voluntary action block. Otherwise no trials were excluded.

Voluntary actions increased apparent motion perception, as shown in Figure 2. A Bayesian multilevel logistic regression[5] model showed that voluntary actions increased apparent motion perception ($\hat{\beta}$ action = 0.51, 95% CI [0.07, 0.99], posterior probability = 98.8%, z[6] = 2.50, p = 0.01). We estimated the magnitude of the perceptual shift by comparing the average 50% motion perception thresholds (point of subjective equality, PSE) between conditions. The PSE was 19 ms higher in the voluntary action condition, indicating that people perceived apparent motion with longer ISI in the voluntary action condition ($PSE_{voluntary}$ = 113 ms, 95% CI [84, 142]; $PSE_{no\ action}$ = 95 ms, 95% CI [60, 126]; difference in PSE (voluntary action – no action) = 19 ms, 95% CI [2, 38]). The posterior probability for a positive shift in PSE was 98.3%.

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[5] We used minimally informative priors to constrain the parameter estimates on the log-odds scale. We used Normal(0, 100) distributions as priors for the population-level (fixed) regression coefficients, $Cauchy^+(0, 4)$ priors for the participant-level (random) coefficient SDs. We also estimated the model using standard maximum likelihood methods (Bates, Mächler, Bolker, & Walker, 2015), which led to identical conclusions. For parameters estimated with the Bayesian model, we report posterior means ($\hat{\beta}$) and their associated 95% Credible Intervals (CI; the central 95% of values in the respective marginal posterior distribution.) All Bayesian inference was done via Hamiltonian Monte Carlo sampling as implemented in the Stan programming language, and the posterior samples were analyzed using R (Bürkner, 2017; R Core Team, 2017; Stan Development Team, 2016).

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

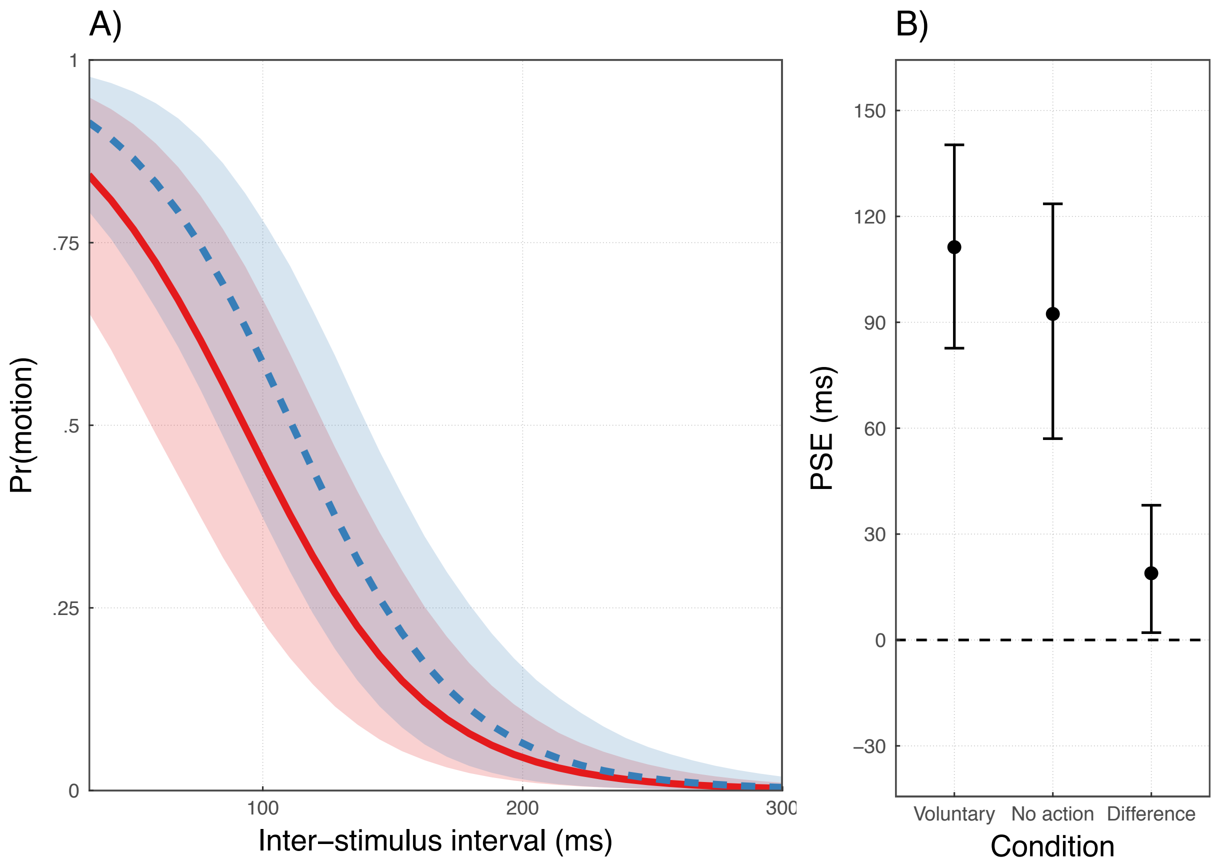

Figure 2.2. Results from the apparent motion task, Experiment 1.

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

Interval estimation

Before analyzing the interval estimation data, we removed 29 trials—out of a total of 3040—because they had responses outside the accepted range (1 – 500ms). One participant quit the study before the interval estimation task, resulting in 19 participants' data included in the analysis. We analyzed the interval estimation data using a Bayesian multilevel linear regression model. As expected from previous literature on intentional binding (Engbert et al., 2007), interval estimates were shorter in the voluntary action condition (Figure 3). On average, participants gave 25 ms shorter estimates in the voluntary action condition (95% CI [-41, -9.4], $t_{(18)} = -3.47$, $p = 0.003$). ISI and action condition did not interact.

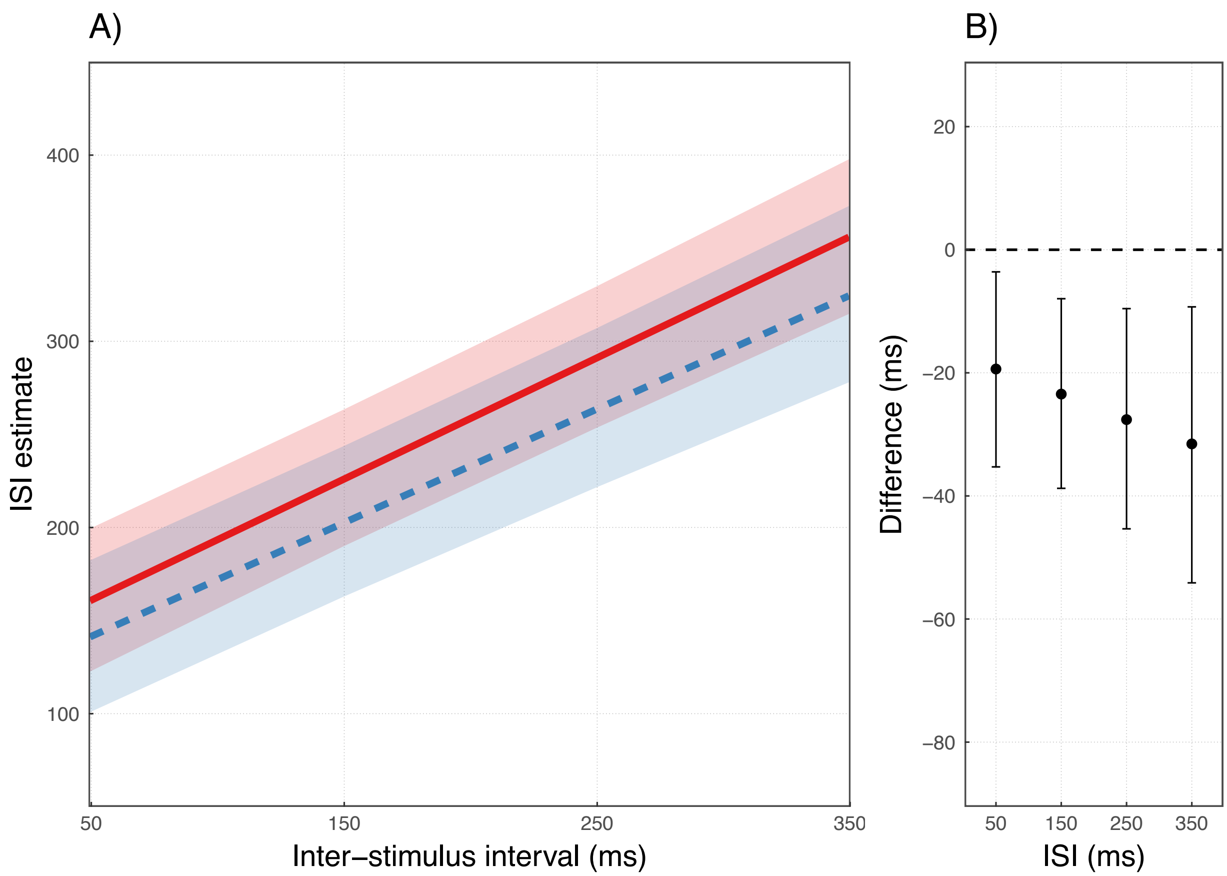

Figure 2.3. Results from the interval estimation task, Experiment 1.

A) Average model-predicted interval estimates for the no action (red) and voluntary action (blue, dashed) conditions, with 95% CIs as light shades. **B)** Difference in interval estimates (voluntary action – no action) for each ISI, error bars are 95% CIs.

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

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

Experiment 2

Method

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

Participants

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

Ternus display task

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

Participants completed the experiment individually on a Dell desktop computer, running at a 75hz refresh rate, in a dark testing room. They were seated approximately 60cm from the monitor and wore headphones throughout the study. At the beginning of the study, the participants were instructed that the experiment was about different types of motion percepts. Before the experiment, they read the following instructions: "In this task, we ask you to observe brief visual stimuli on the screen, and report what you see. Specifically, we will show you a display called the Ternus display. In the Ternus display, you will see two circles flash on the screen, then another two circles flash slightly to the right of the first two circles. This can lead to two different types of motion perception. The first, called element motion, looks as if only the outermost circle moved from the left-most position to the right-most position, while the middle circle remained stationary. The second type of motion perception is called group motion and looks as if both circles moved right." They also saw an image similar to Figure 1B. They then passively observed 34 demonstration trials of the Ternus display; 12 trials with short intervals (0 and 13ms ISI), 12 trials with long intervals

(120 and 133ms ISI), and 10 trials with the intervals used in the actual experiment. Participants did not provide responses during the demonstration trials.

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

Results and Discussion

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

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

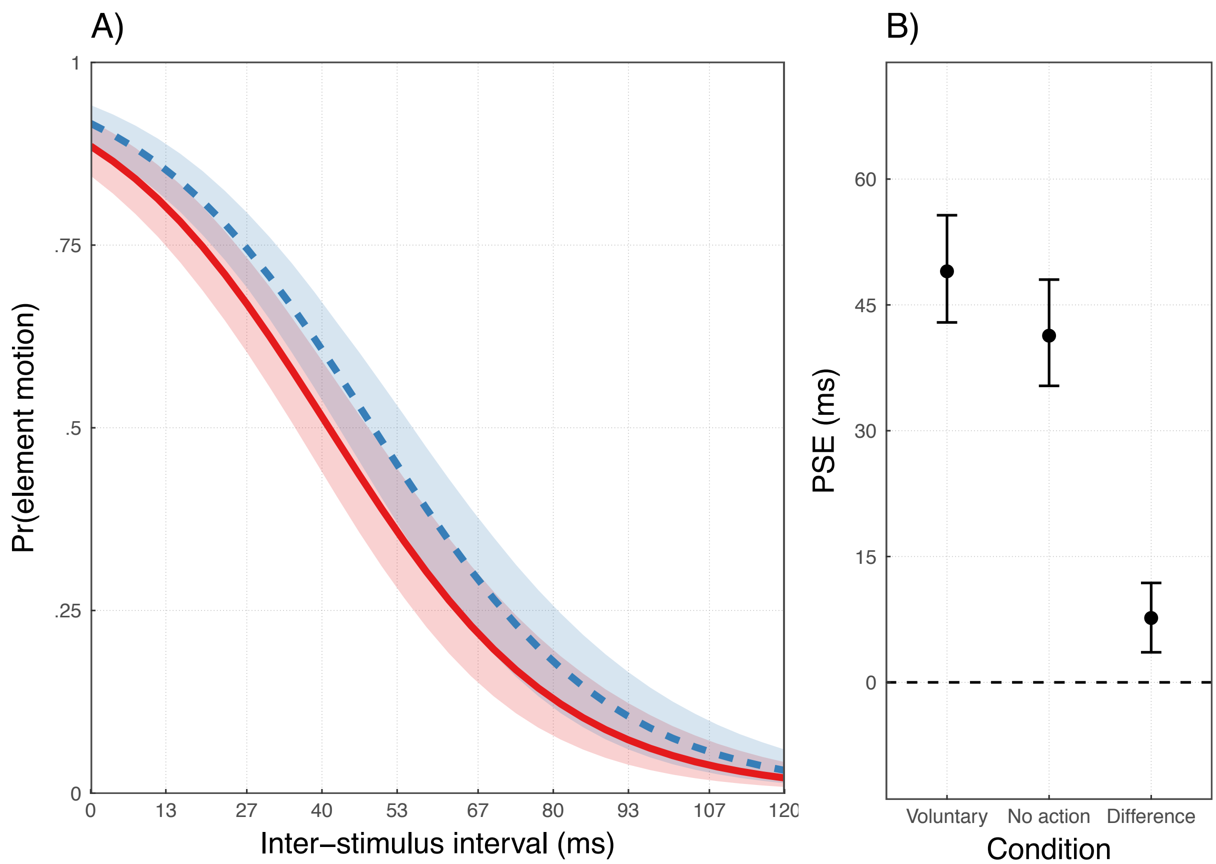

Figure 2.4. Results from the Ternus display task, Experiment 2a.

A) Average model-predicted probabilities of element motion responses for the no action (red) and voluntary action (blue, dashed) conditions, with 95% CIs as light shades. **B)** Points of subjective equality in both experimental conditions, and their difference (voluntary action – no action; error bars are 95% CIs).

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

Experiment 2b

Method

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

Participants

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

Results and Discussion

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

The results replicated those of Experiment 2: A Bayesian multilevel logistic regression model[1] showed that voluntary actions increased element motion perception ($\hat{\beta}$ action = 0.25, 95% CI [0.002, 0.503], posterior probability = 97.6%, $z = 2.17$, $p = 0.03$). We quantified the perceptual shift using the 50% element motion thresholds (point of subjective equality, PSE). The PSE was

6.3 ms higher in the voluntary action condition than in the passive condition ($PSE_{voluntary}$ = 50 ms, 95% CI [44, 57]; $PSE_{no\ action}$ = 44 ms, 95% CI [35, 53]; difference between PSE (voluntary – no action) = 6.3 ms, 95% CI [0.13, 12.7]). The posterior probability for a positive difference in PSE was high (97.72%).

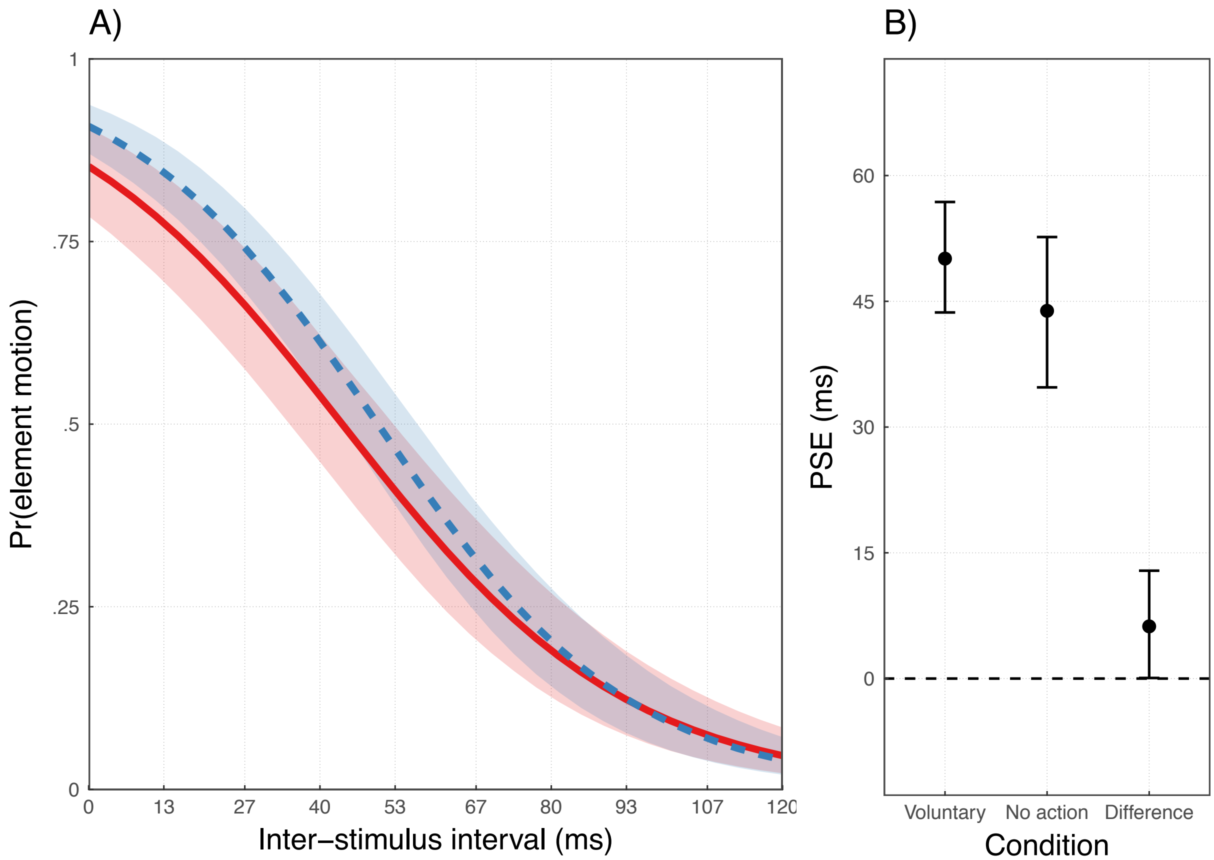

Figure 2.5. Results from the Ternus display task, Experiment 2b.

A) Average model-predicted probabilities of element motion responses for the no action (red) and voluntary action (blue, dashed) conditions, with 95% CIs as light shades. **B)** Points of subjective equality in both experimental conditions, and their difference (voluntary action – no action; error bars are 95% CIs).

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

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

To evaluate the differential preparation explanation of our results, we conducted a final control experiment in which we manipulated participants' ability to prepare and predict the stimuli. We employed the manipulations used in classic preparation experiments (e.g. Behar & Adams,

1966) using warning signals to alert participants about an upcoming stimulus, as the basis of our design. In this final experiment, participants observed the Ternus display in two conditions: (1) in the warning signal condition, in which they heard a tone 1 second before the onset of the first visual stimulus, and (2) in the no warning signal condition, in which they were not forewarned about the onset of the visual stimuli. By the differential preparation view of our effects, the first (warning) condition should be similar to the voluntary action condition and the second (no warning) condition should be like the passive condition. If ability to prepare or predict mediates the effects of action, people should perceive element motion at longer ISIs in the warning condition, than in the no warning condition.

Experiment 3

Method

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

Participants

Thirty-six Columbia University undergraduate students participated in the experiment in exchange for course credit. The experiment was approved by the Columbia University Internal

Review Board and was carried out in accordance with the Psychonomic Society ethical guidelines and with the Declaration of Helsinki.

Results and Discussion

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

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

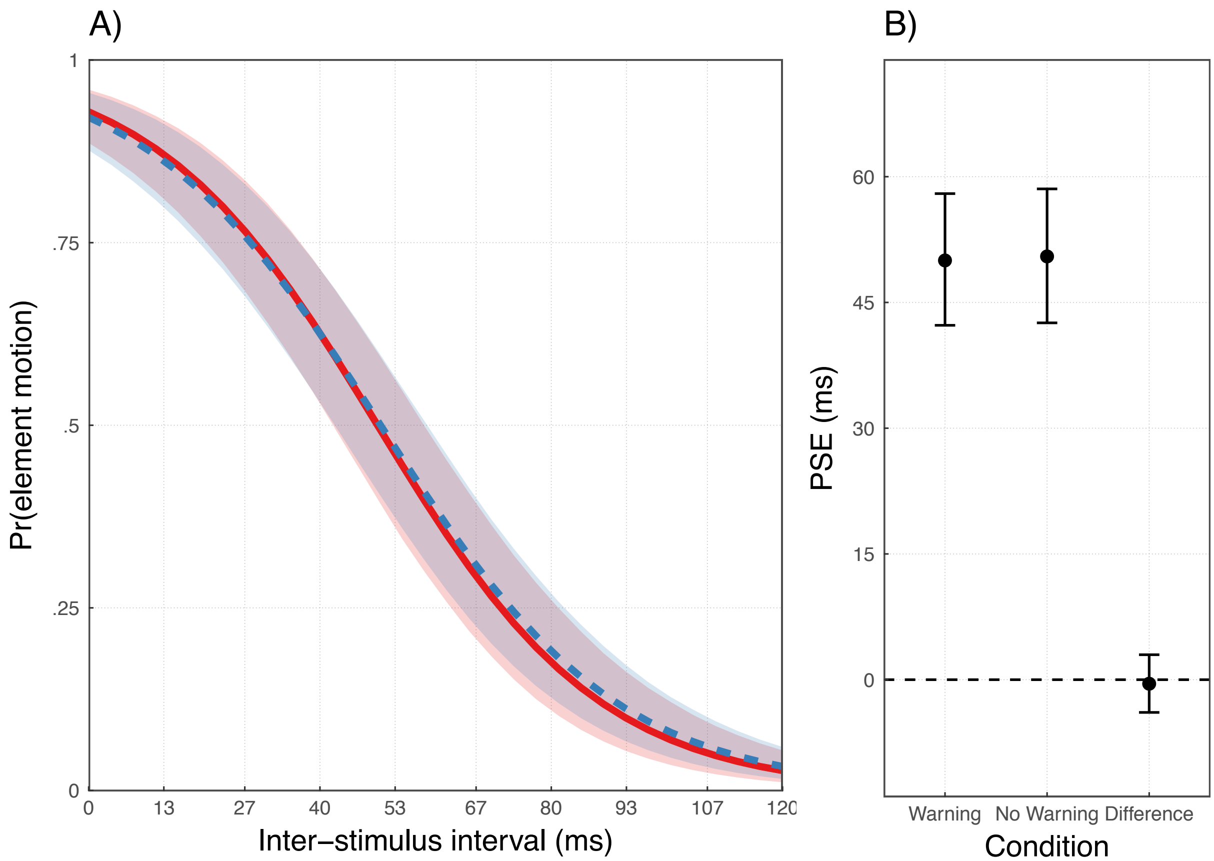

Figure 2.6. Results from the Ternus display task, Experiment 3.

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

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

3 than was the effect of voluntary action in Experiments 2a ($\hat{\beta}$ = -0.38, 95% CI [-0.67, -0.08]) and 2b ($\hat{\beta}$ = -0.30, 95% CI [-0.59, -0.01]). In summary, these results showed that the warning signal had no effect on participants' perception of the visual illusions, reinforcing the idea that voluntary actions modulated perception of the illusions through changes in time perception, instead of changes in preparation or predictability of the stimuli.

Discussion

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

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

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

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

However, our results do not clearly distinguish between this rate-shift explanation, and another one which suggests that the switch component of an internal clock might be implicated instead. According to internal clock models (Gibbon, Church, & Meck, 1984), a separate switch mechanism (sometimes called a gate) initiates the period during which pulses should be accumulated to working memory for duration judgments. Another possible explanation for subjective time compression, then, is that following action the switch initiates pulse accumulation later than in a control condition, leading to fewer ticks being accumulated in a given time period. Results from Experiment 1 (interval estimation task) were not fully in favor of this explanation, however, because a delayed switch mechanism would lead to a constant shortening of subjective durations, whereas we observed a shortening effect that increased with the to-be-estimated interval (**Figure 2.3**). Furthermore, the clock slowing account would predict that the subjective interval shortening effect would scale up with the judged duration more steeply than was observed in that experiment. Therefore, although suggestive of an internal clock modulation, more research is needed to determine the exact mechanism of the shortened interval estimates—and increased motion perception—observed in the current experiments, and to possibly better distinguish between the clock rate shift and delayed switch explanations.

Role of Temporal Contiguity and Uncertainty

Introduction

The intentional binding effect is thought to be closely related to the sense of control people experience over their voluntary actions, and the effects of those actions (Haggard et al., 2002). Subsequently, many researchers have used intentional binding as an implicit measure of this 'sense of agency' (Moore & Obhi, 2012). However, the precise nature and underlying mechanisms of this temporal distortion remain poorly understood.

One subsequent question has therefore been to ask whether the distorted timing judgments reflect a retrospective process—a modulation of how the temporal properties of events are remembered—or an online perceptual process whereby temporal processing is modulated during the events themselves, leading to changes in how other events are perceived. Although it remains a possibility that intentional binding reflects a retrospective effect, more recent studies have found evidence to the contrary. Some of these studies have suggested that the effect reflects a general slowing of subjective time, such that the actions and effects are separated by less subjective time, with measurable consequences in other perceptual processes during the events (Vuorre & Metcalfe, 2017; Wenke & Haggard, 2009). This general slowing of subjective time hypothesis stands in contrast to another proposed mechanism of the effect, whereby subjective durations remain constant, but the timing of the events relative to one another is recalibrated with no consequences to general temporal processing during the events (Stetson, Cui, Montague, & Eagleman, 2006).

The subjective time slowing hypothesis makes a specific prediction about time-dependent perception following voluntary action: If intentional binding reflects a general slowing of subjective time, then any two events—not just action and its effect—should appear closer together in time following voluntary action. Two previous studies investigating this hypothesis found support for this prediction, one using temporal simultaneity judgments to assess cutaneous temporal discriminability following action. This study found that people need longer intervals between two electric shocks to correctly perceive them as non-simultaneous when those shocks followed voluntary action, in comparison to when the shocks followed a passive movement (Wenke & Haggard, 2009).

Another study used visual illusions of motion that depend critically on the interval separating two stimulus frames (inter-stimulus interval; ISI)—specific motion illusions occur only when the ISI is very short. The reasoning behind these experiments was that if voluntary actions lead to a general slowing of subjective time, then objectively longer ISIs would appear as shorter in perception, and therefore the motion illusions should persist at longer objective ISIs. Accordingly, the results showed that people perceive visual illusions of motion at longer ISIs following voluntary action versus passive observation (Vuorre & Metcalfe, 2017). Additionally, other related studies have shown that action preparation can slow subjective time (Hagura, Kanai, Orgs, & Haggard, 2012; Tomassini, Gori, Baud-Bovy, Sandini, & Morrone, 2014). However, one study did not find evidence for a general clock slowing mechanism in the context of the intentional binding effect (Fereday & Buehner, 2017)[7]. Nevertheless, the weight of evidence from these studies suggests that the subjective time slowing hypothesis, possibly caused by a slowing of an internal clock (Wenke & Haggard, 2009), is a plausible explanation of the intentional binding effect.

[7] Contrary to the other experiments reviewed here, which measured perception following voluntary actions, this experiment asked participants to verbally estimate the interval between two events that were inserted in the action-effect interval. This difference may explain the different results, although more research is needed to tease out the precise explanation between these conflicting findings.

Regardless of whether a general time-slowing mechanism underlies the intentional binding effect, the studies reviewed above show that actions impact perception (or judgments) of subsequent stimuli in predictable ways: For example, actions led to visual stimuli appearing closer together in time such that motion illusions were perceived at longer ISIs compared to passive viewing (Vuorre & Metcalfe, 2017). The purpose of the present experiments was to investigate to what extent factors that are known to influence intentional binding also modulate actions' impact on perception of visual motion illusions. Specifically, we examined to what extent temporal contiguity and predictability modulate action's effects on perception of illusory visual motion.

Previous studies have shown that temporal contiguity impacts intentional binding: In the first study to report the intentional binding effect, it was also observed that an increased delay between action and its effect decreased the intentional binding effect (Haggard et al., 2002). That is, compared to a short (250ms) action-effect interval (AEI), the intentional binding effect was smaller when the AEI was increased (650ms). This finding suggests that the temporal binding effect is strongest when the action and effect are separated by time intervals commonly found for operant actions in ordinary life. That is, the expectation that action's effects usually occur almost immediately after the action may modulate the effect (e.g. Eagleman & Holcombe, 2002).

However, this modulation of intentional binding by temporal contiguity seems to depend on the actual intervals used in the experiment, and at least one study has found increased intentional binding for longer as compared to shorter AEIs (Ruess, Thomaschke, & Kiesel, 2017; see also Buehner, 2012; Wen, Yamashita, & Asama, 2015). Nevertheless, if temporal contiguity of action and effect modulates the intentional binding effect, we would expect it to also have an effect on action's effects on visual motion perception. That is, illusory perception of motion (associated with short ISIs) should persist at longer ISIs when there is no delay between action and effect, when compared to increasing delays between action and effect. This prediction follows from the hypotheses that the intentional binding effect is explained by a subjective time slowing mechanism, and that the previously observed modulation of motion illusions reflects intentional binding.

Second, temporal predictability of action's effects sometimes modulates intentional binding: When AEI is varied within a block, making the effect temporally less predictable, the intentional binding effect is smaller than in blocks where AEI is fixed, and therefore the action's effect more predictable. This suggests that intentional binding depends on the ability to accurately predict when the action's effect occurs (Haggard et al., 2002). However, the effect of temporal predictability on binding also seems to depend on the specific AEIs used in the experiment, such that predictability increases binding for short AEIs, but decreases for long AEIs (Ruess et al., 2017). Therefore, we do not make a strong prediction about the direction of this effect, but note that a complex interaction such as the one reported in Ruess et al., (2017) would complicate the interpretation of intentional binding as a straightforward marker of the sense of control.

Both of these temporal modulations of the intentional binding effect highlight its connection to the subjective experience of control: In line with the effects of temporal contiguity on intentional binding, contiguity also affects people's ratings of control. A multi-study analysis of seven experiments' data found that increasing the delay between an action and its (visual) effect strongly reduced ratings of control, but only when participants were specifically instructed to focus on when the effect happened (Chambon, Moore, & Haggard, 2014; Chambon, Wenke, Fleming, Prinz, & Haggard, 2013; Sidarus & Haggard, 2016; Sidarus, Vuorre, & Haggard, 2017a, 2017b; Voss, Chambon, Wenke, Kühn, & Haggard, 2017). These studies therefore confirm that temporal contiguity affects control ratings—but only when participants focus on the contiguity—and suggest that the extent to which intentional binding is associated with the experience of control, temporal contiguity should modulate intentional binding. However, the relationship between explicit feelings of control and intentional binding may be less straightforward as initially thought (Dewey & Knoblich, 2014), precluding any strong predictions about the current experiments based only on previous control rating experiments. Nevertheless, they reinforce the prediction that—to the extent that intentional binding and explicit feelings of control are positively related—longer action-effect intervals should lead to decreased perception of visual motion illusions.

Therefore, the aim of the current study was to extend the findings of Vuorre and Metcalfe (2017), and investigate the extent to which temporal contiguity and predictability affect action's impact on visual motion illusions, as measured by the Ternus-Pikler display (Ternus, 1926; Figure 3.1). In the first frame of this display, three horizontally aligned circles are presented such that two of them are on the left of a central fixation point, and one is on the right. After a variable inter-stimulus interval (ISI), an identical set of three circles is presented again, but this time shifted to the right such that one circle is on the left of the central fixation point, and two on the right. If the ISI is very short, people perceive *element* motion, which appears as the originally leftmost circle leapfrogging over the other circles to land on the rightmost position of the second circle triplet. With longer ISIs, people perceive *group* motion, in which all three circles appear to move to the right as a group. Participants always initiated the display with a button press, and we varied the ISI and whether the display followed the button press immediately, or after a delay (action-effect interval; AEI).

We conducted two experiments to examine the extent to which temporal contiguity and predictability affect motion perception in the Ternus-Pikler display. In both Experiments, there were two types of blocks of trials. In one, the AEI was set to 0ms, and in the other, AEI was pseudorandomly varied between 0, 400, and 800ms. Experiment 2 was identical except that AEIs of 0, 200, and 400ms were used. This design allowed us to investigate the effect of AEI contiguity (the AEI duration in the variable AEI block) and AEI predictability (across the fixed 0ms AEI and random blocks) on motion perception in the Ternus-Pikler display. Because intentional binding has been shown to decrease—suggesting diminished temporal compression—with longer AEIs and increased AEI variability (Haggard et al., 2002), we hypothesized that participants would observe element motion at longer ISIs when a) the AEI was shorter and b) more predictable. Additionally, we asked participants to rate their experienced control over the stimuli after each block and predicted that control ratings would be higher in the fixed AEI blocks.

Experiment 1

Method

Participants

Fifty-six Columbia University undergraduates participated for course credit. We used the same exclusion criteria as in a previous related report (Vuorre & Metcalfe, 2017): Participants with less than a 10% decrease in element motion responses from the shortest to longest ISI were rejected, because they either were not attending to the task appropriately[8], or were otherwise not sensitive to the different motion types. This exclusion criteria led to 20 participants being rejected, and a final sample of 36 participants included in the analyses below. The experiment was approved by the Columbia University Internal Review Board and was carried out in accordance with the Psychonomic Society ethical guidelines.

[8] For example, one participant talked on the phone during the experiment, although all participants were asked to leave their belongings outside the testing room.

Stimuli and Task

Participants observed the Ternus-Pikler display (Figure 3.1; Ternus, 1926) which consists of two frames of three horizontally aligned black circles on a uniform mid-tone grey background (the circles were faded to background with a Gaussian mask with SD = 1.5°, center-to-center distance = 1.2°, duration = 67ms), with a central fixation cross. In the first frame, two of the three circles are on the left side of the fixation cross. In the second frame, two circles are on the right of the fixation cross. The two frames are separated by an inter-stimulus interval (ISI), during which only the fixation cross is visible. With a short ISI, the display tends to elicit a perception of "element motion", in which the initially leftmost circle moves to the rightmost position of the second frame. Element motion may look as if the outermost circle slides through, or jumps over, the middle two circles. With longer ISIs, the display tends to elicit "group motion" in which the triplet appears to move rightward as a group.

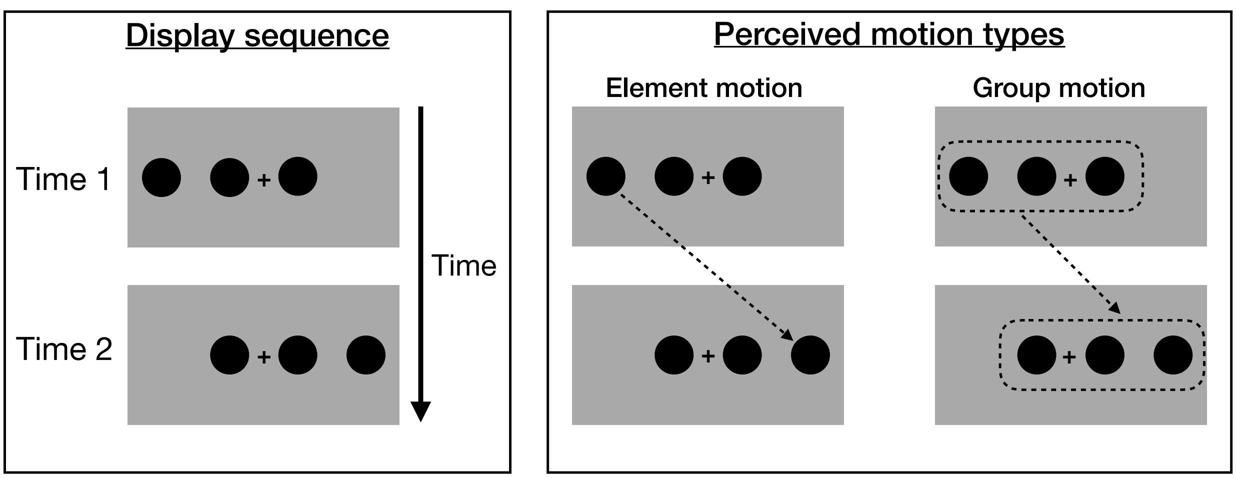

Figure 3.1. Ternus-Pikler display.

The dashed lines indicate perceived motion and grouping and were not visible to the participants.

Each trial begun with a black fixation cross in the middle of the screen. Participants were instructed to press a button whenever they wished, after the fixation cross had appeared. The button press initiated the Ternus-Pikler display. 1.2s after the offset of second triplet of circles, the fixation cross disappeared and the words 'Element' and 'Group' became visible to prompt a response. After the participant's response, the chosen response was highlighted for 300ms, and a new trial started after 1.2 seconds.

Design

ISI was pseudorandomly varied between trials: we used 7 levels of ISI (0, 17, 33, 50, 67, 83, 100ms). There were two types of blocks: In the *fixed* block, the first frame always onset immediately after the participant's button press. In the *random* block, there was a variable action-effect interval (AEI; 0ms, 400ms, 800ms; randomized between trials) between the button press and the onset of the first stimulus. Participants completed one fixed and three random blocks in a randomized order; each block had 105 trials (2 participants completed 126 trials). Before each block type, they read the following instructions:

> *In the next trials, your button press will cause the display to happen immediately* [*after a small delay* (in the AEI blocks)]. *Press the mouse button whenever you wish to do so, when the fixation cross is visible. Please press the mouse button only once per trial.*

After each block, the participants provided a rating of control using the number keys on a keyboard ("How in control did you feel over the visual stimuli during the preceding set of trials? 1 = Lowest control, 9 = Highest control"), and were then instructed to take a break before proceeding if they wanted to. Participants completed the experiment alone in a dark testing room, on an Apple iMac computer running at 60Hz, and wore headphones throughout the experiment to reduce distraction.

Results

Action-Effect Interval duration

Temporal contiguity between action and effect was manipulated within the random AEI blocks, in which the first stimulus frame was presented after a 0, 400, or 800ms delay following the participant's button press. We used multilevel logistic regression[9] to model the element motion responses as a function of ISI and AEI and calculated 50% element motion thresholds (PSE; point of subjective equality) from this model. The PSE was greater for 0ms AEI (31ms, 95% CI[10] = [23, 40]) than both the 400ms (27ms, 95% CI = [20, 35]; difference = 4ms, 95% CI = [1, 8], $p^+ = .99$[11]) and 800ms AEIs (27ms, 95% CI = [20, 35]; difference = 4ms, 95% CI = [0, 8], $p^+ = .98$), suggesting that element motion perception is sustained at longer ISIs when there is no delay between action and the onset of the stimuli. The ISI x AEI interaction for both AEI durations ($b_{isi:400ms} = -0.04$, SE = 0.04, 95% CI = [-0.12, 0.04]; $b_{isi:800ms} = -0.01$, SE = 0.04, 95% CI = [-0.08, 0.06]) was very small and plausibly equal to zero (both credible intervals narrowly lassoed zero), suggesting similar sensitivity to ISI in all AEI conditions. These results are shown in Figure 3.2.

[9] Responses were coded as [0 = group motion; 1 = element motion], ISI was entered as a predictor in terms of the number of frames at 60Hz [0 - 6]. All parameters were treated as varying between subjects. The Bayesian model was fitted using MCMC sampling as implemented in the Stan software, and post-processed with R (Bürkner, 2017; Carpenter et al., 2017; R Core Team, 2017).

[10] Bayesian Credible Interval.

[11] We use p^+ to indicate the posterior probability that the contrast is positive.

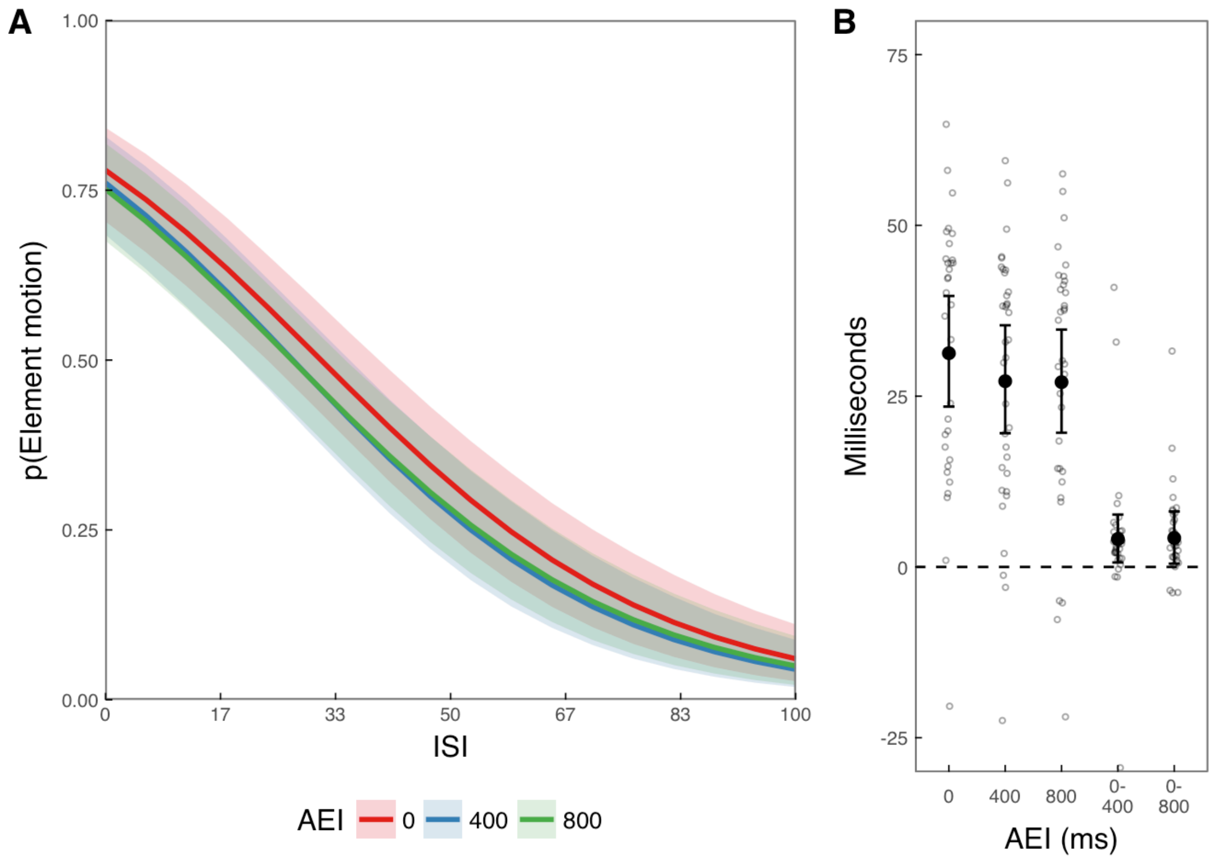

Figure 3.2. Element motion responses as a function of AEI duration, Experiment 1.

A) Population-level regression lines of element motion responses as a function of inter-stimulus interval (ISI) and AEI duration (three colors). **B**) Points of subjective equality (PSE), and their differences, for the three AEIs. Small points are participant-specific estimates. Shades and bars are 95% CIs.

Although there was evidence of an increased PSE in the 0ms AEI in contrast to the two AEI delay conditions, these increases were small. However, the magnitude of the effect was similar to that in a previous report of action's effects on element motion perception (Vuorre & Metcalfe, 2017). As shown in Figure 3.3, these effects were consistent across participants, suggesting that while the effect on average is small, it is robust across subjects. Further, the effects of 400ms and 800ms delays on the PSE were very similar (Figure 3.3C), suggesting that element motion PSEs do not gradually decrease as a function of AEI duration, but rather that any delay (within the ranges investigated in this study) has a constant effect on the PSE.

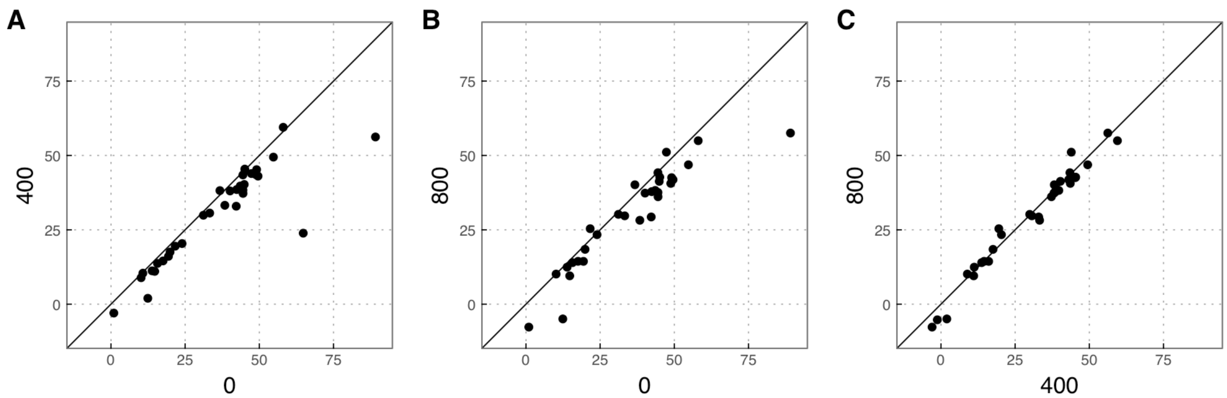

Figure 3.3. Within-subject scatter plots of PSEs, Experiment 1.

The points indicate posterior mean PSEs for each subject, for a given pair of AEI delays. The x and y axes indicate different AEI delays. The diagonal line indicates identical PSE for the AEI delays on the x and y axes; points falling below the diagonal indicate subjects whose PSE was greater in the AEI delay on the x axis compared to the AEI delay on the y axis.

Action-Effect Interval Uncertainty

To investigate the impact of temporal predictability on element motion responses, we compared 0ms AEI trials between the random and fixed blocks. We fit a multilevel logistic regression model with ISI and block (random AEI, fixed AEI) as predictors (see footnote 9) and calculated PSEs from this model. The PSE was greater in the random AEI blocks (32ms, 95% CI = [23, 41]) than the fixed AEI block (28ms, 95% CI = [19, 37]), but this difference was not plausibly different from zero (-4ms, 95% CI = [-10, 3], $p^+ = .12$), suggesting that PSEs are similar across conditions of temporal uncertainty. The ISI x block interaction estimate was slightly positive but uncertain and plausibly zero ($b_{isi:random} = 0.08$, SE = 0.09, 95% CI = [-0.08, 0.26]), suggesting that sensitivity to ISI is similar across conditions of temporal uncertainty. These results are shown in Figure 3.4.

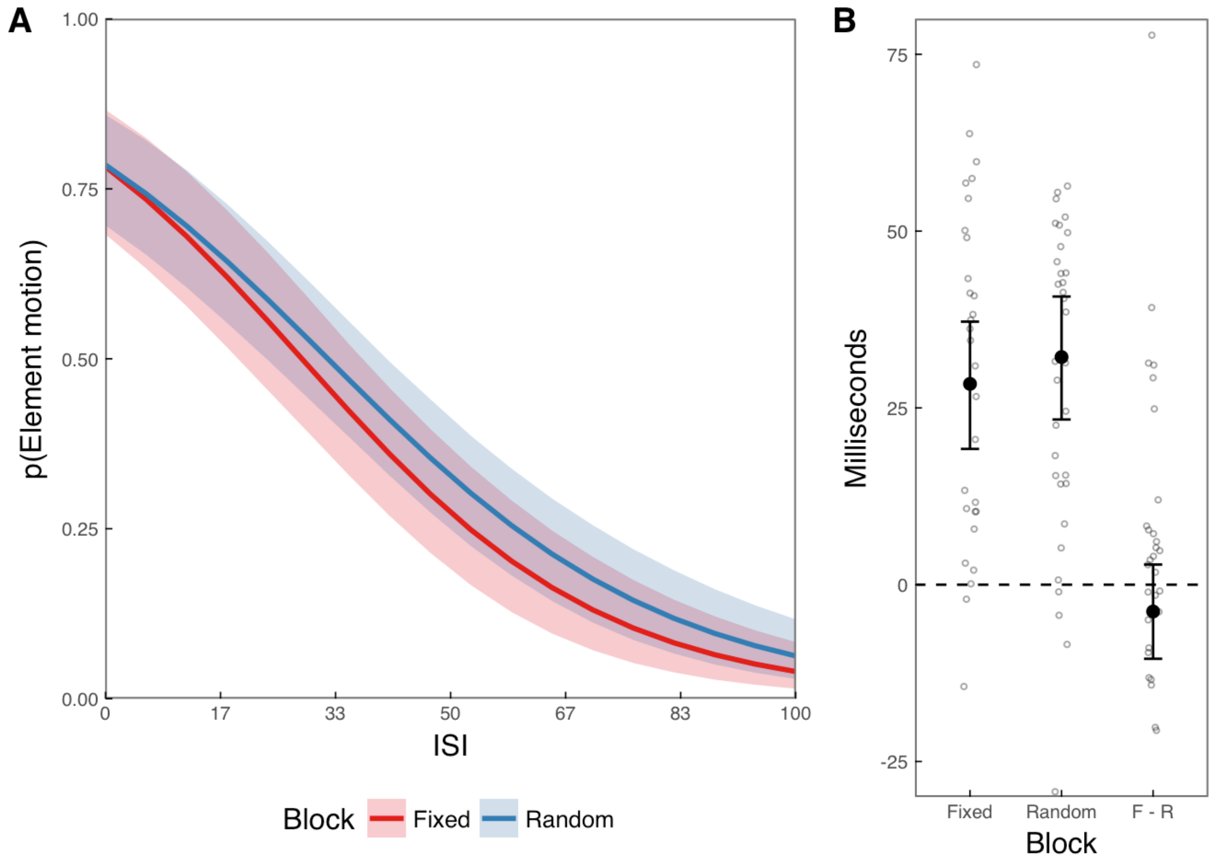

Figure 3.4. Element motion responses as a function of AEI uncertainty, Experiment 1. **A**) Population-level regression lines of element motion responses on inter-stimulus interval as a function of AEI variability (block). **B**) Points of subjective equality (PSE), and their differences, for the two blocks. Small points are participant-specific estimates. Shades and bars indicate 95% CIs.

Contrary to our prediction, the random AEI block led to similar PSEs (with a small trend toward increasing PSEs) than the fixed block, suggesting that a block-wise manipulation of temporal uncertainty does not modulate motion perception in the Ternus-Pikler display. The slightly positive ISI x block interaction suggested decreased sensitivity to ISI in the temporally unpredictable (random AEI) block. This latter finding suggests at least a partial attentional explanation, whereby participants might attend to the stimuli less when they are temporally unpredictable, which in turn might decrease the effect of ISI on element motion perception. However, this suggestion is speculative because of the great uncertainty in the interaction estimate.

Control ratings

Participants provided control ratings at the end of each block. We expected the control ratings to be decreased in the random AEI blocks when compared to the fixed AEI block. However, because previous research shows that this effect may only occur when participants are specifically told to attend to the temporal contiguity of action and effect, we did not make a strong hypothesis regarding this effect. Nevertheless, and contrary to our expectation, there was no difference in control ratings between the two blocks (b_{random} = 0.19, SE = 0.32, 95% CI = [-0.44, 0.83]; Figure 3.5).

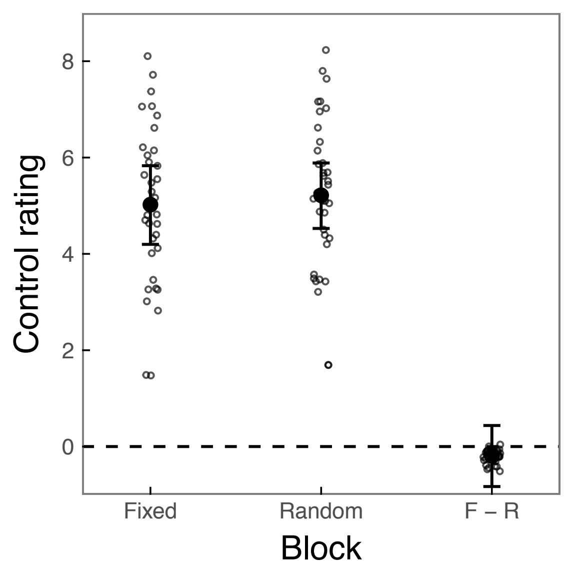

Figure 3.5. Control ratings for the two AEI variability blocks, Experiment 1.

Large points and bars indicate posterior means and 95% CIs; small points are posterior means of subject-specific estimates. F-R is the difference between fixed and random blocks.

Although previous studies have sometimes reported decreased explicit control ratings for stimuli that are temporally unpredictable, others have highlighted that this effect only occurs when participants are specifically told to attend to the temporal variation (Sidarus, Vuorre, & Haggard, 2017b). Our participants were attending to a difficult visual task, instead of assessing their experienced control of the stimuli on a trial-by-trial basis, likely explaining why we found no difference in control ratings between blocks. These results suggest that the relationship between intentional binding—and more generally, actions' impact on temporal perception—and explicit control ratings is not straightforward (e.g. Dewey & Knoblich, 2014).

Discussion

Experiment 1 investigated the effects of temporal delay and predictability on perception of voluntary action-initiated illusory motion displays. Results indicated that temporal predictability (whether actions caused the stimuli after a fixed or random duration) had little or no impact on motion perception in the Ternus-Pikler display. Action-effect interval duration did have a small but consistent impact on element motion responses: Participants saw element motion at longer ISIs when their actions caused the Ternus-Pikler display immediately, when compared to conditions in which there was a small delay (400 or 800ms) between action and stimulus onset.

However, other studies investigating the intentional binding effect have sometimes used AEIs shorter than 400ms (e.g. Haggard et al., 2002), and suggest that AEI duration might interact with predictability (Ruess et al., 2017) in modulating binding. For these reasons, we conducted Experiment 2 to extend Experiment 1's findings to shorter AEIs (0, 200, and 400ms). Experiment 2 also allowed us to directly replicate the 400ms AEI delay effect observed in Experiment 1.

Experiment 2

Method

Participants

Forty-four Columbia University undergraduates participated for course credit. We used the same exclusion criteria as in Experiment 1, which led to a final sample of 34 participants included in the analyses. The experiment was approved by the Columbia University Internal Review Board and was carried out in accordance with the Psychonomic Society ethical guidelines.

Stimuli and Task

The task and stimuli were identical to Experiment 1, except that we used AEIs of 0, 200, and 400ms.

Results

Action-Effect Interval duration

We modeled the data identically to those of Experiment 1. The PSE was greater for 0ms AEI (33ms, 95% CI = [26, 40]) than 200ms (28ms, 95% CI = [21, 35]; difference = 5ms, 95% CI = [3, 8], $p^{+} > .99$) and 400ms (29ms, 95% CI = [21, 35]; difference = 4ms, 95% CI = [1, 7], $p^{+} > .99$), suggesting that element motion perception was sustained at longer ISIs in the no delay condition. The 0-400ms difference also directly replicated the finding from Experiment 1. There was no ISI x AEI delay interaction for either AEI duration ($b_{isi:200ms} = 0.05$, SE = 0.04, 95% CI = [-0.04, 0.12]; $b_{isi:400ms} = 0.02$, SE = 0.04, 95% CI = [-0.05, 0.10]), suggesting similar sensitivity to ISI in all AEI conditions. These results are shown in Figure 3.6. Furthermore, as shown in Figure 3.7, these effects were consistent across participants.

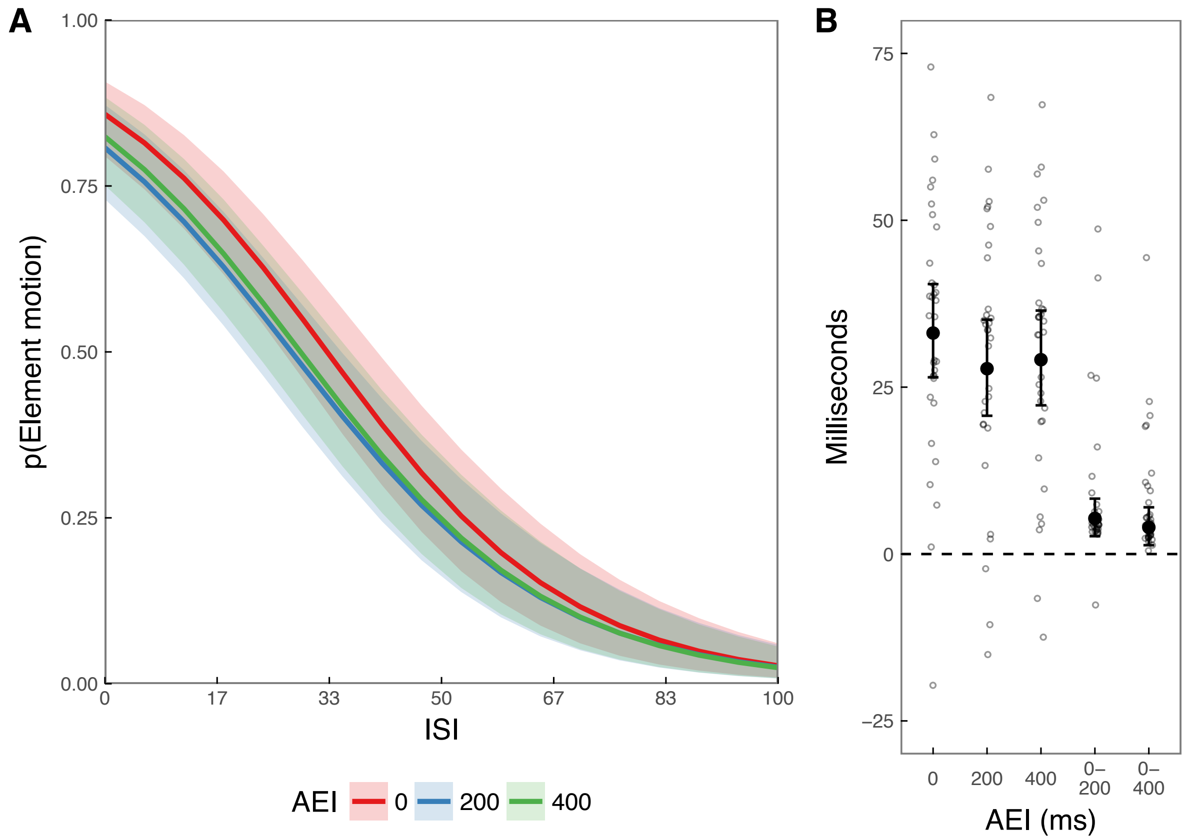

Figure 3.6. Element motion responses as a function of AEI duration, Experiment 2.

A) Population-level regression lines of element motion responses on inter-stimulus interval (ISI), as function of AEI duration (three colors). **B**) Points of subjective equality (PSE) and their differences across AEIs. Small points are participant-specific estimates. Shades and bars indicate 95% CIs.

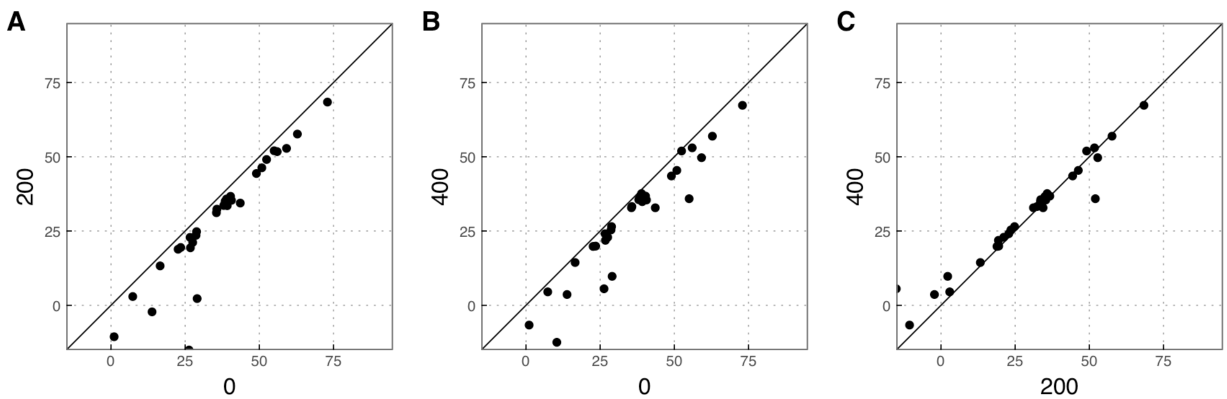

Figure 3.7. Within-subject scatter plot of PSEs, Experiment 2.

Points indicate posterior mean PSEs for each subject, for a given pair of AEI delays. The x and y axes indicate different AEI delays. The diagonal line indicates identical PSE between the AEI delays on the x and y axes; points falling below the diagonal indicate subjects whose PSE was greater in the AEI delay on the x axis compared to the AEI delay on the y axis.

Action-Effect Interval Uncertainty

The results of the block-wise manipulation of temporal uncertainty were similar to findings from Experiment 1. In Experiment 2, the PSE was greater for the random AEI blocks (34ms, 95% CI = [27, 40]) than the fixed AEI block (30ms, 95% CI = [24, 36]). However, unlike in Experiment 1, this difference was plausibly different from zero (-3ms, 95% CI = [-6, -1], $p^+ < .01$), suggesting that people see element motion at longer ISIs when the AEI is variable. However, because we did not hypothesize the effect in this direction, and the pattern was absent in Experiment 1, we hesitate to interpret these results as strong evidence for this effect. The ISI x block interaction estimate was slightly positive but uncertain ($b_{isi:random}$ = 0.03, SE = 0.04, 95% CI = [-0.04, 0.10]), suggesting that sensitivity to ISI was similar across blocks. These results are shown in Figure 3.8.

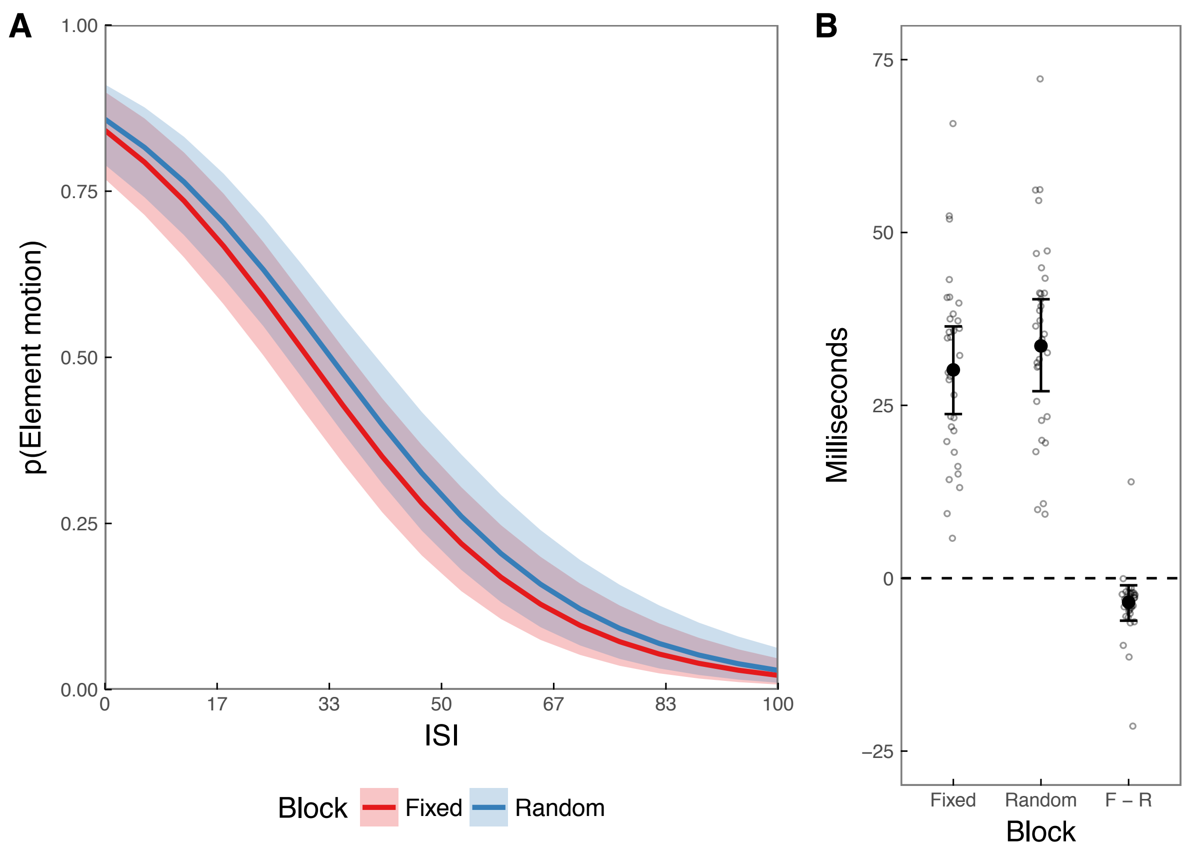

Figure 3.8. Element motion responses as a function of AEI uncertainty, Experiment 2.

A) Population-level regression lines of element motion responses on inter-stimulus interval, as function of AEI variability (block). B) Points of subjective equality (PSE), and their differences, for the two blocks. Small points are participant-specific estimates. Shades and bars indicate 95% CIs.

Control Ratings

There was again no effect of temporal predictability (block) on participants control ratings (b_{random} = -0.22, SE = 0.35, 95% CI = [-0.92, 0.48]; Figure 3.9). Taken together with Experiment 1, these results suggest that participants' feelings of control are not affected by whether the visual stimuli are temporally predictable or not. These results are consistent with prior literature suggesting that temporal uncertainty affects control ratings only when participants are asked to specifically attend to this feature, which we did not do. Further, the complicated visual task would likely make such attending difficult.

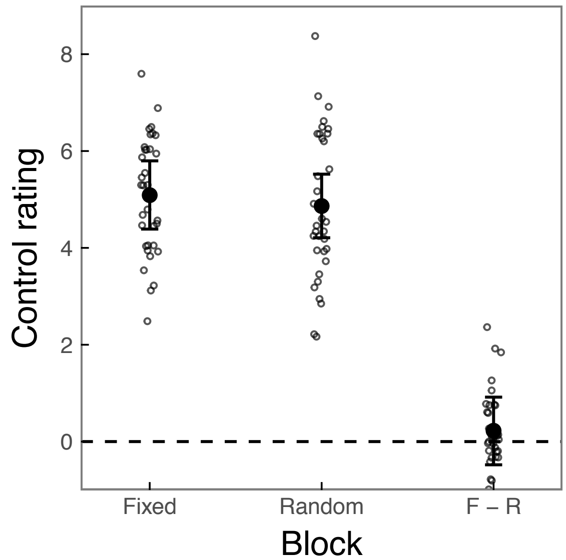

Figure 3.9. Control ratings for the two AEI variability blocks, Experiment 2.

Large points and bars indicate posterior means and 95% CIs of the population level parameters; small points are posterior means of subject-specific estimates. F-R indicates the difference between the fixed and random blocks.

Does AEI Effect Vary Across ISIs?

Above, we conducted standard psychophysical analyses of element motion responses using logistic regression. These models allowed us to quantify the effect of AEI on element motion perception in terms of temporal shifts of the 50% probability of reporting element motion (point of subjective equality; PSE). However, these standard models allowed AEI to interact linearly with inter-stimulus interval (i.e. linearly decreasing/increasing effect of AEI as function of ISI), and it is possible that AEI has unique effects at different levels of ISI (i.e. a non-linear AEI x ISI interaction). Although such a model would be less parsimonious, it is possible that the perceptual consequences of voluntary action may change in a non-linear manner depending on when the stimuli occur following action (Wenke & Haggard, 2009). For this reason, we conducted an exploratory analysis investigating the effects of the various AEI delays at each ISI duration. We estimated a logistic model of element motion responses that included AEI as a predictor and allowed it to vary randomly across participants and ISIs (i.e. a "crossed random effects" model). This model therefore allowed us to compare the effect of AEI across levels of ISI in a manner that avoids problems with multiple comparisons (Gelman, Hill, & Yajima, 2012). We fit this model to the combined data of Experiments 1 and 2, and included an Experiment by ISI interaction to allow differences between experiments[12].

The results of this model showed that there was an average effect of each AEI across the ISIs used in these two experiments (b_{200ms} = -0.21, SE = 0.08, 95% CI = [-0.37, -0.03]; b_{400ms} = -0.17, SE = 0.05, 95% CI = [-0.27, -0.07]; b_{800ms} = -0.16, SE = 0.08, 95% CI = [-0.31, -0.01]), supporting the main results regarding AEI as discussed above. Interestingly, the effects of these AEIs also varied across ISIs, as shown by the standard deviation parameters (*s*) that describe the variation of AEI effects across ISIs (s_{200} = 0.11, SE = 0.09, 95% CI = [0.00, 0.35]; s_{400} = 0.06, SE = 0.06, 95% CI = [0.00, 0.20]; s_{800} = 0.09, SE = 0.08, 95% CI = [0.00, 0.29]). The observed average proportions of element motion responses, and differences in the average proportions across AEIs, are shown in Figure 3.10.

As can be seen in Figure 3.10, element motion responses were more frequent in the 0ms AEI condition than in any of the AEI delay conditions, and this pattern was somewhat consistent across ISIs. The difference between 0ms AEI and any AEI delay was greatest at 17-50ms ISI, suggesting that the effect of temporal uncertainty on element motion perception was greatest at roughly the

[12] We also estimated the model to Experiments 1 and 2 separately, yielding identical conclusions.

50% element motion perception threshold (Figure **3.2** and Figure **3.6**). Further, there was no consistent pattern in differences between the effects of each of the three AEI delays, suggesting that the duration of the delay—within the delays included in our Experiments—is not important. In summary, the results of this analysis indicated that while the effects of AEI are somewhat consistent across ISIs, any delay between a participant's button press and the visual stimuli most strongly reduces element motion responses when the ISI is 17-50ms.

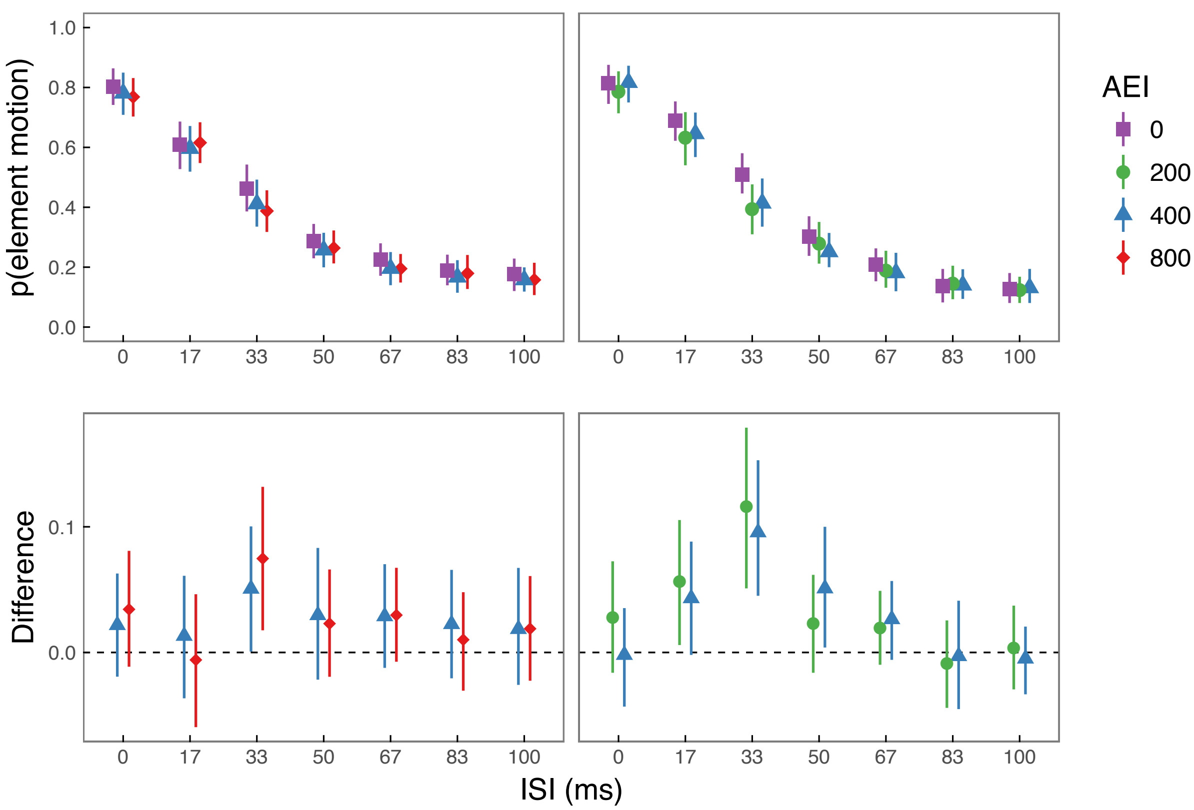

Figure 3.10. AEI-ISI interaction.

Observed average element motion proportions (top row) and differences in average element motion proportions (bottom row) for each ISI, and across levels of action-effect interval (AEI). Left column: Experiment 1, right column: Experiment 2. The differences in the bottom panels indicate the average proportion of element motion at the AEI delay indicated by the color subtracted from the average element motion proportion at 0ms AEI. Points and bars indicate means and 95% bootstrapped confidence intervals across participants.

Discussion

We conducted two experiments to investigate the effects of temporal contiguity and predictability on motion perception in the context of voluntary action, using the Ternus-Pikler display. We found that temporal contiguity (the delay between action and stimulus), but not temporal predictability (variability in delay), affects which type of motion is perceived: When there is no delay between action and effect, participants observe element motion—type of motion illusion observed when ISI is short—at longer ISIs when compared to conditions in which there is a small delay between action and effect. This effect is fairly consistent across participants, and exploratory analyses suggested that reduced delay led to increased element motion perception specifically at intermediate values of ISI.

Previous experiments investigating the intentional binding effect—the subjective shortening of time intervals following voluntary action—suggested that a general clock slowing mechanism may account for the effect (Vuorre & Metcalfe, 2017; Wenke & Haggard, 2009; but see Fereday & Buehner, 2017). These studies compared time-sensitive perception (visual motion illusions, Vuorre & Metcalfe, 2017; touch discrimination, Wenke & Haggard, 2009) between conditions where participants voluntarily initiated the stimuli or observed them passively, and found that voluntary actions led to persistence of motion illusions, and subjective simultaneity of touch, at longer ISIs when compared to conditions where voluntary action was absent. Other studies have looked at factors that modulate the intentional binding effect (as measured with the Libet clock methodology, see Haggard et al., 2002), and found that longer, and more variable, intervals separating action and effect lead to reduced binding. Therefore, this study investigated whether these same factors influence the perceptual consequences of voluntary action reported in Vuorre and Metcalfe (2017), a finding which would further support the slowed clock hypothesis.

Our findings partially supported that hypothesis: When there was no delay between action and effect (the visual stimuli), participants observed more element motion than when there was a delay, similarly to what was reported about the intentional binding effect. However, increased temporal uncertainty has been found to sometimes reduce intentional binding (Haggard et al., 2002; but see Ruess et al., 2017), but it had no impact on element motion perception in Experiment 1, and a small effect in the opposite direction in Experiment 2.

Lastly, we also asked participants to evaluate their experienced control over the visual stimuli and predicted that participants would feel more in control following a block of trials in which their actions immediately produced the stimuli, in contrast to a block of trials where there was a variable delay between action and stimulus. The results did not support this expectation, possibly because the motion perception task required a great deal of attention, and focused attention on the experience of control has been shown to modulate temporal uncertainty's effect of control ratings (Sidarus, Vuorre, & Haggard, 2017b).

We cannot entirely rule out the possibility of attention as an important contributing factor in the current results (e.g. Ruthruff & Pashler, 2001). Any manipulation involving participants' uncontrolled (by the experimenter) movements is likely to involve an attentional component, for example by directing attention away from the visual task to one's moving hand. In our task, participants might have experienced a brief attentional blink following their button presses, which in turn would have impacted visual processing immediately following one's action, but not if there was a short delay between one's action and the visual stimulus. It is also possible that the surprising result of the block-wise uncertainty manipulation in Experiment 2 was due to attention:

Participants might have been able to attend the visual stimuli more closely in the temporally predictable condition, thus increasing the PSEs in the unpredictable blocks. However, it is not at all clear why attention would shift motion perception in this direction: Presumably, attending to a visual task makes one's perceptual inference more accurate, and neither group or element motion is a particularly accurate description of the physical stimuli, leading to further questions about the directionality of the effects if attention, indeed, was the underlying mechanism. Nevertheless, future experiments should specifically target attention as a potential explanation of intentional binding specifically, and its hypothesized perceptual consequences more generally.

In conclusion, the experiments presented here further lend credibility to the hypothesis that an underlying shift in temporal processing is responsible for the intentional binding effect: Manipulations that affect binding were confirmed to affect perceptions of illusory visual motion in a manner that would be predicted by a general clock-slowing mechanism of intentional binding (Fereday & Buehner, 2017; Wenke & Haggard, 2009): Participants observed more element motion at longer ISIs when stimuli immediately followed their actions, versus when a small delay was inserted between action and stimulus, exactly mirroring previous findings on the intentional binding effect.

Conclusions

The purpose of this dissertation was to investigate the possible mechanisms underlying the intentional binding effect, and its perceptual consequences. Namely, we hypothesized (Wenke & Haggard, 2009) that voluntary actions and their effects are reported as having occurred closer together in time than two similar but passively observed events because voluntary actions temporarily slow an internal timekeeper. According to internal clock models of time perception, there is an internal clock that measures the magnitude of elapsed time by generating evenly spaced ticks, and the number of ticks indicates the elapsed duration (see, e.g., Gibbon, Church, & Meck, 1984; Wearden, 2008). If actions slowed this internal clock, any subsequent stimuli would be separated by fewer ticks and would thus appear as closer together in subjective time. We presented participants with sequences of visual stimuli which, when presented at short separating intervals, result in specific illusions of motion. The slowed clock hypothesis therefore predicted that this inter-stimulus interval would appear as shorter following voluntary action, and motion illusions would persist at longer intervals. Results presented in Chapter 2 confirmed this prediction, and therefore suggested that clock-slowing is a plausible mechanism underlying the intentional binding effect.

Chapter 3 investigated whether manipulations of temporal contiguity and predictability, which are known to impact intentional binding, have similar effects on action's impact on illusory visual motion perception. Specifically, if the effects observed in Chapter 2 resulted from the same mechanism as intentional binding—namely, slowing of an internal clock—then these two factors, temporal contiguity and predictability, should also impact actions' effects on visual motion illusions. Results showed that similar to reducing the magnitude of the intentional binding effect, increasing the interval between action and effect decreased participants' reports of observing illusory element motion (see Figure 3.1).

More generally, the present results suggest that actions' impact on time perception and visual perception is not limited to retrospective modulation, or how the events are remembered. In other words, in the context of the intentional binding effect, people do not simply misremember when their actions, or those actions effects, occurred. Instead, voluntary operant actions modulate how events are perceived over time. This modulation has robust consequences, as shown here using visual illusions of motion.

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