Action, Prediction, or Attention: Does the "Egocentric Temporal Order Bias" Support a Constructive Model of Perception?

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Arts

Approved October 2020 by the
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ARIZONA STATE UNIVERSITY

December 2020

ABSTRACT

Temporal-order judgments can require integration of self-generated action-events and external sensory information. In a previous study, it was found that participants are biased to perceive one's own action-events to occur prior to simultaneous external events. This phenomenon, named the "Egocentric Temporal Order Bias", or ETO bias, was demonstrated as a 67% probability for participants to report self-generated events as occurring prior to simultaneous externally-determined events. These results were interpreted as supporting a feed-forward, constructive model of perception. However, the empirical data could support many potential mechanisms. The present study tests whether the ETO bias is driven by attentional differences, feed-forward predictability, or action. These findings support that participants exhibit a bias due to both feed-forward predictability and action, and a Bayesian analysis supports that these effects are quantitatively unique. Therefore, the results indicate that the ETO bias is largely driven by one's own action, over and above feed-forward predictability.

ACKNOWLEDGMENTS

This work was partially funded by SigmaXi and the Global Sport Institute.

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CHAPTER 1

INTRODUCTION

In everyday life, we must temporally integrate our own action-events and proprioception with externally generated sensory information. This integration becomes particularly important in fast-paced sports such as soccer and basketball, where players frequently make judgments concerning the order of nearly-simultaneous events. However, even on a day-to-day basis, these disagreements about temporal order can be observed anywhere from traffic at stop signs, to students raising their hands in class, to precisely timed key presses in a video game.

Recently, considerable research has investigated the phenomena of subjective time (Allman, Teki, Griffiths, & Meck, 2014; Blewett, 1992; Eagleman, 2008; Eagleman & Holcombe, 2002; Gibbon, 1986; Kim et al., 2010; Sackett, Meyvis, Nelson, Converse, & Sackett, 2009; van Wassenhove, Buonomano, Shimojo, & Shams, 2008; Zauberman, Kim, Malkoc, & Bettman, 2009). In particular, many researchers have investigated a temporal illusion that action-events are temporally "bound" to its causal action, referred to as "intentional binding" (Desantis, Roussel, & Waszak, 2014; Ebert & Wegner, 2010; Haering & Kiesel, 2012, 2014, 2015; Haggard, Clark, & Kalogeras, 2002; Moore & Haggard, 2010; Moore & Obhi, 2012; Yabe, Dave, & Goodale, 2017). In the classic paradigm for studying intentional binding, a participant performs an action which is followed by a delay and then some kind of action-event (such a light turning on, a sound being emitted, etc.) (Haggard et al., 2002). These studies have shown that participants adapt to the delay between the action and action-event and subsequently perceive the delay to be attenuated, resulting in a perception of the action and action-event as having happened closer together in time. This effect has been correlated with sense of agency across several studies, and demands preconditions of both voluntary action and perceived causality (Desantis, Hughes, & Waszak, 2012; Eagleman & Holcombe, 2002; Haering & Kiesel, 2012; Haggard et al., 2002; Wen, Yamashita, & Asama, 2015). A fundamental consistency across intentional binding experiments is the delay between the action and action-event. Indeed, this delay has been one of the primary experimental manipulations in intentional binding literature, leading to phenomena such as the subjective perception of reverse causality (Stetson, Cui, Montague, & Eagleman, 2006; Timm, Schönwiesner, SanMiguel, & Schröger, 2014).

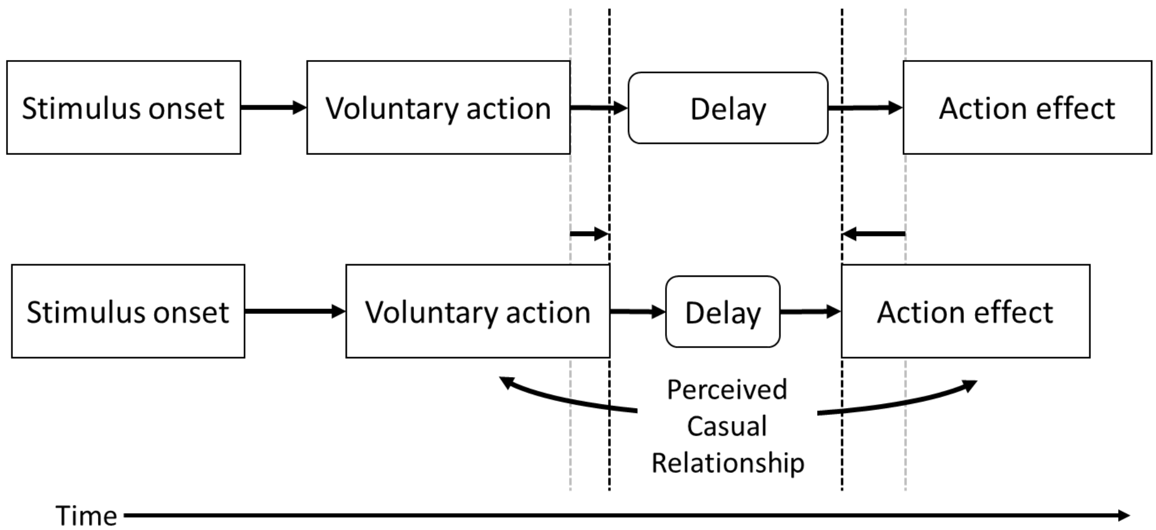

Figure 1. Classical intentional binding paradigm, where an artificial delay between a voluntary action and its action effect is perceptually attenuated. Binding requires both the perception of causality and sense of agency over the action effect.

However, such an artificial delay between an action and action-event is inconsistent with the majority of our physical interactions with the world around us. While delays may be observed while interacting with computerized systems (sometimes frustratingly so), when we pick up a cup, play a note on a piano, or hit a baseball with a bat, there is no perceptible delay between the action and action-event. Until recently, there has been no evidence of a subjective temporal bias extending to physical interactions with no delay between the voluntary actions and its action-event.

In order to investigate whether subjective temporal order is observed in ecological interactions of temporal order such as those seen in sports, we conducted an experiment where participants made a temporal order judgment between a haptic action-event they caused and an externally generated haptic event (Tang & McBeath, 2019, 2020). In this paradigm, two participants sat across a table from one another. Following the flash of a light cue, participants tapped one another on their opposite hand (Figure 2 & 3). Both participants then made independent, anonymous temporal order judgments by pressing a button on a controller. This way, neither participant could tell what their partner's judgment was. Participants were not allowed to communicate with their partner during the experiment, had no visual information about their partner's movements prior to the touch, and received no feedback between trials.

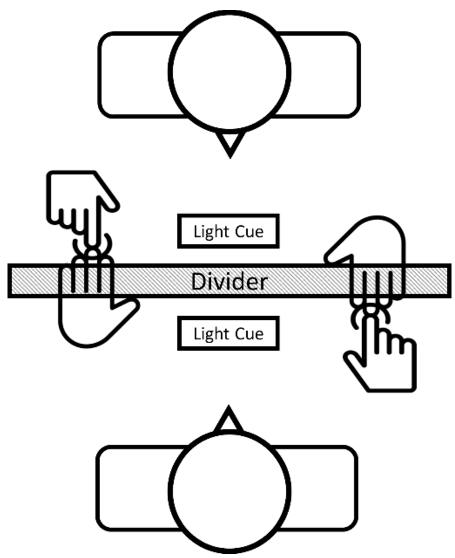

Figure 2. Top-down cartoon illustration of the egocentric temporal order paradigm. Two participants sit across a table and tap each other's hand when the light cue flashes. Both participants then make independent temporal order judgments about which touch happened first. Participants cannot see one another, are not allowed to communicate, and are given no feedback between trials.

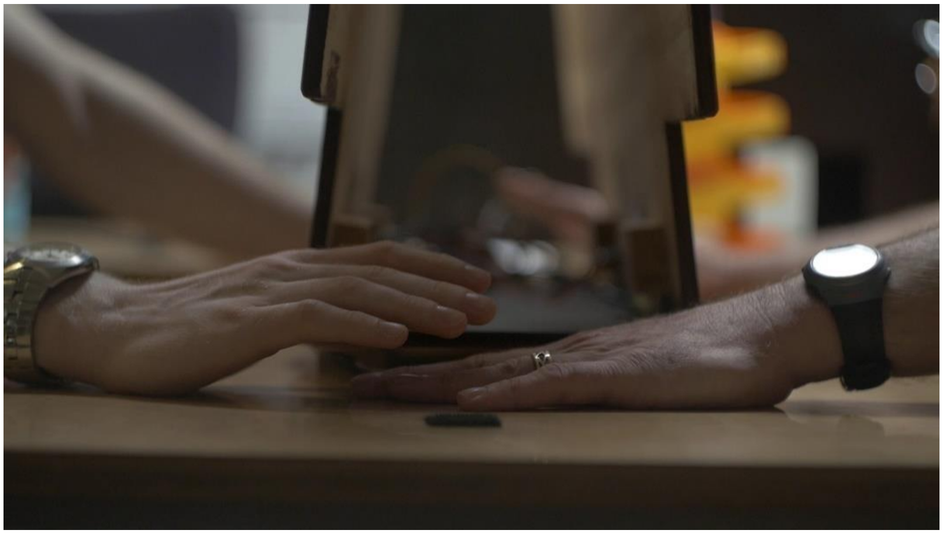

Figure 3. A side view of the egocentric temporal order test set up used by Tang and McBeath (Tang & McBeath, 2019). Two participants get ready to tap one another's hands. Photo taken by Rob Ewing of Arizona State University.

We observed a robust bias for participants to report that their touch was before their partner's touch, even when touches were simultaneous. Additionally, we found that this effect generalizes independent of whether the stimulus source is human or nonhuman (solenoid), and extends to other types of sensory inputs, such as audition (Tang & McBeath, 2019). This phenomena, referred to as the Egocentric Temporal Order (ETO) bias, demonstrates that disagreements in temporal order judgments may arise from individuals experiencing differing accounts of subjective time. This finding is interpreted as supporting a feed-forward, stream-of-consciousness model of perception (James, 1890). However, the data are insufficient to discriminate between this explanation and others (prior entry, intentional binding, etc.).

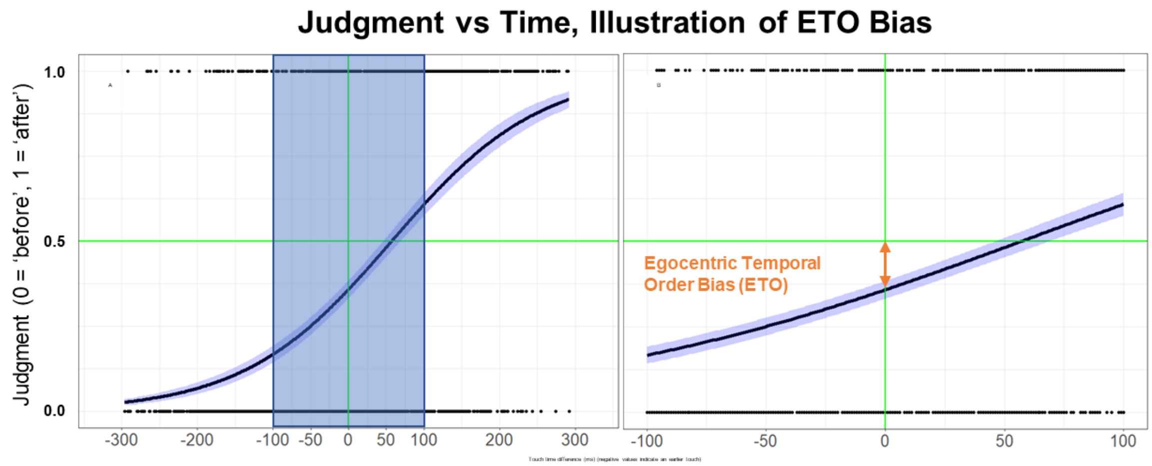

Figure 4. Visual demonstration of Egocentric Temporal Order (ETO) bias. The black line indicates an individual's probability of thinking they touched before or after the other participant, as a function of the time difference between the touches. The vertical green line indicates the time at which both touches from both participants were truly simultaneous; the horizontal green line indicates where participants are equally likely to respond "I touched first" or "they touched first". The black dots on the bottom and top of each graph correspond to individual responses, coded "I touched first" and "they touched first", respectively. (A) Binary logistic model of participants' temporal order judgments vs time. (B) A zoom in on the blue area of Figure 2A. The ETO bias is represented by the vertical-judgment offset from the origin, respectively.

In the present study, we investigate the underlying mechanisms driving the ETO bias. Specifically, we investigate the effects of 1) action, 2) feed-forward predictability, and 3) attentional differences. Explanations for each proposed mechanism are explained henceforth:

1. The bias occurs due to differences in how one's own action-events are perceived, as compared to externally generated events. The mechanisms may be the same as those driving intentional binding, the binding effect of an action-intention and its subsequent action-event. Intentional binding has been studied extensively, but experiments have focused primarily on the binding between the action and action-event, and its relationship to sense of agency, and its underlying mechanism of action remains largely unknown

(Desantis et al., 2012; Ebert & Wegner, 2010; Moore & Haggard, 2010; Moore & Obhi, 2012; Timm et al., 2014).

2. The bias supports a constructive, “stream of consciousness”, model of perception, wherein an internal feed-forward model of reality is experienced in real-time, and external stimuli are perceptually delayed (James, 1890). This model is further supported by findings from the intentional binding literature that disruption of the pre-supplementary motor area, a brain region associated with prediction, attenuates the temporal binding of the action-event (Moore, Ruge, Wenke, Rothwell, & Haggard, 2010), and can explain phenomena such as the perceived temporal reorganization of events associated with predictable sensory outcomes (Cavazzana, Penolazzi, Begliomini, & Bisiacchi, 2015; Desantis, Waszak, Moutsopoulou, & Haggard, 2016). Our previous research supports that this additional processing time for external perceptual information manifests as a roughly 50 ms offset between a predictable self-generated events and unpredictable external stimulus events (Tang & McBeath, 2019). We note that this model is consistent with human 20 Hz motor coordination speed limit for tasks like drumming and coordinating stadium waves and is further supported by our approximately corresponding 20 Hz visual flicker and auditory fusion rates (McBeath & Krynen, 2015).
3. Attentional focus moderates the bias. Attention is known to moderate stimulus intensity and other factors such a reaction time (Okubo, Laeng, Saneyoshi, & Michimata, 2010; Schechter & Buchsbaum, 1973; Spence & Parise, 2010; Wu et al., 2017). When making temporal order judgments comparing two events in close temporal proximity, it is likely that participants tend to focus their attention on their own action, rather than external ones, but egocentric control and action may not be required. The ETO bias could occur principally as a function of when and where people focus their attention. Therefore, it could be that the ETO bias is simply a manifestation of prior entry, first described by E.B. Titchener in 1908: “the object of attention comes to consciousness more quickly than the objects which we are not attending to” (Holt & Titchener, 2006; Spence & Parise, 2010).

In order to discriminate between these explanations, we developed three experiments. In all three experiments, the participant judges the temporal order between two events. By varying one of the events in action (having the participant generate the stimulus themselves), predictability (the participant can see and predict when the stimulus will occur), and attention (the participant is instructed to attend to one stimulus over the other), we can determine the underlying mechanism of the ETO bias. It is important to note that action, predictability, and attention are interdependent. Specifically, one can predict and must attend to their own action, and one must attend to a stimulus to predict it.

	Experiment 1	***Experiment 2***	***Experiment 3***
Action	Yes	No	No
Prediction	Yes	Yes	No
Attention	Yes	Yes	Yes

Table 1. A table showing the three experiments and their experimental manipulations.

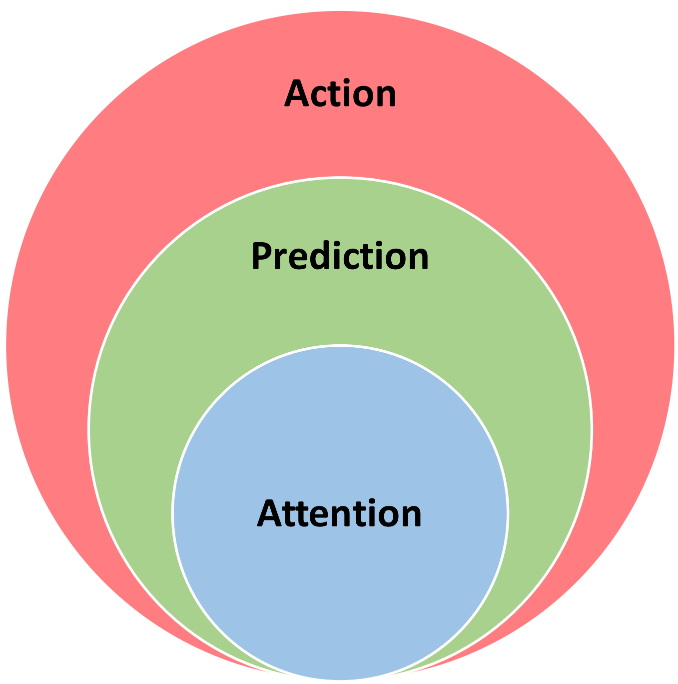

Figure 5. Visual representation of interdependencies of each experiment. Same information as shown in Table 1.

CHAPTER 2

DATA

COLLECTION AND PROCESSING

In each experiment, participants experienced two touches and then made a temporal order judgment about which touch occurred first. Touch timing data were collected using piezoelectric sensors fixed to participant's index fingers on both hands. The sensors relayed force readings to an Arduino microprocessor. When the sensors were touched, the readings were measured, and the Arduino sent the times of the touches to a computer to save the data into a .csv text file.

More specifically, the time of each touch was calculated with the fractional peak latency measure, a common method for measuring onset latency in electrophysiological data (Kiesel, Miller, Jolicœur, & Brisson, 2008; Luck, 2014). This measures the time of each touch as the time point at which the output of the piezoelectric sensor reaches half of the peak amplitude for that trial. One of the advantages of this method is remains robust to high frequency noise (Luck, 2014), which in this case allows it to ignore small motion artifacts made by the participant.

For each trial, the time difference between touches is always calculated as the time of the experimentally manipulated touch (always the participant's right hand) to the control touch (always the participant's left hand). Therefore, a negative time difference indicates that the experimentally manipulated touch occurred prior to the control touch. Trials where the two touches were not within 500 milliseconds of each other were removed, as well as when touches were not within 5000 milliseconds of their temporal order judgment (133/5250 or 2.5% of trials).

Temporal order judgments were made immediately after each trial. The participant nonverbally issued their judgment of if the stimulus on their left hand or right hand occurred first by pressing limit switches on their left and right sides, respectively. The apparatus were positioned such that they could click the buttons with their pinky finger, removing the need for them to move their arms between trials. The temporal order judgments are coded such that “0” indicates that the participant responded that the manipulated stimulus occurred first, whereas “1” indicates that the participant responded that the control stimulus occurred first. Participants’ data were removed if judgments were below 50% accuracy (1/33 or 3% of participants).

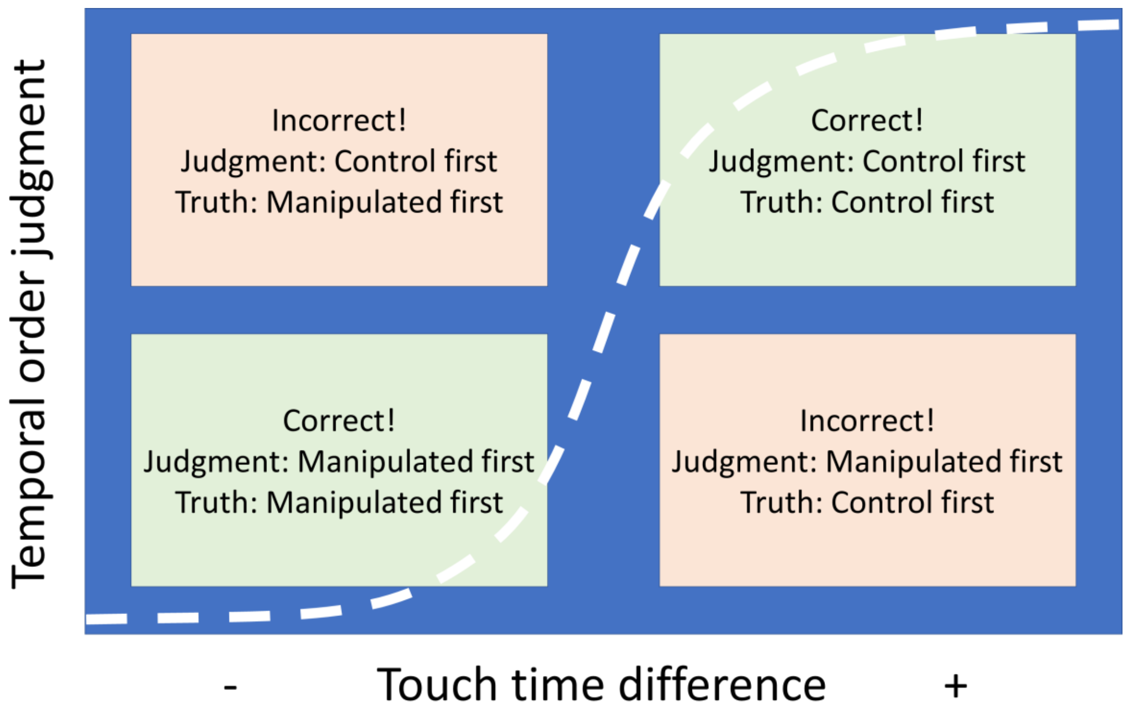

Figure 6. Illustration of the relationship between time difference and temporal order judgments.

DATA ANALYSIS

33 Arizona State University undergraduate psychology students participated in our study. Participants gave written consent to participate and have their data collected. The data are represented with the time difference between stimuli as the independent measure and temporal order judgments as the dependent measure. In all cases, time differences were calculated by taking the manipulated stimuli onset timing and subtracting the control stimuli offset timing. The temporal order judgment represents a binary decision, where the manipulated stimulus is compared to the control stimulus. In this paradigm, a value of 0 represents a decision of “the

manipulated stimulus occurred first", whereas a value of 1 represents a decision of "the control stimulus occurred first". These data are then modeled per experiment using a binary logistic regression model of the form:

$$y = \left(1 + e^{-(\beta_0 + \beta_1 x + \beta_2 \bar{x}_{se})}\right)^{-1} \quad (1)$$

Where β_0 is the y-intercept, β_1 represents the shape of the function, and β_2 is a scaling factor to correct for mean time differences of a given participant in a given experiment. In the context of our study, *x* represents the time difference between the two stimuli, *y* represents the probability of the participant judging the manipulated stimulus as occurring first at any given time difference, and β_0, the y-intercept, represents the probability of a participant judging that the manipulated stimulus occurs first when there is a 0 millisecond difference between stimuli (previous referred to as the ETO bias). An early analysis of the data additionally demonstrated that y varies as a function of the average time difference for each participant (see the Discussion section for explanatory mechanisms for why this might be). Because the average time difference is not a variable of interest for our hypothesis, its inclusion in the model is simply to remove the effects of average time from our analysis. The functional model can therefore be rewritten as:

$$P(Temporal\ Order\ Judgment) = \left(1 + e^{-(Bias + Slope * \Delta Time)}\right)^{-1} \quad (1)$$

In each experimental condition, the ETO bias is captured by the statistical significance of the y-intercept of the model. Functionally, statistical significance of the y-intercept means that the probability of judging the manipulated stimulus as having occurred first when both stimuli occur simultaneously is not equal to chance. Specifically, a negative value of the y-intercept means there is a bias toward perceiving the manipulated stimulus as having occurred first, and a positive value of the y-intercept means there is a bias toward perceiving the control stimulus as having occurred first. Importantly, the logistic regression models are modeled on the experiment level, not on a participant level. The reason for this is due to correlational interference between the average time difference and individual differences on the participant-level of analysis.

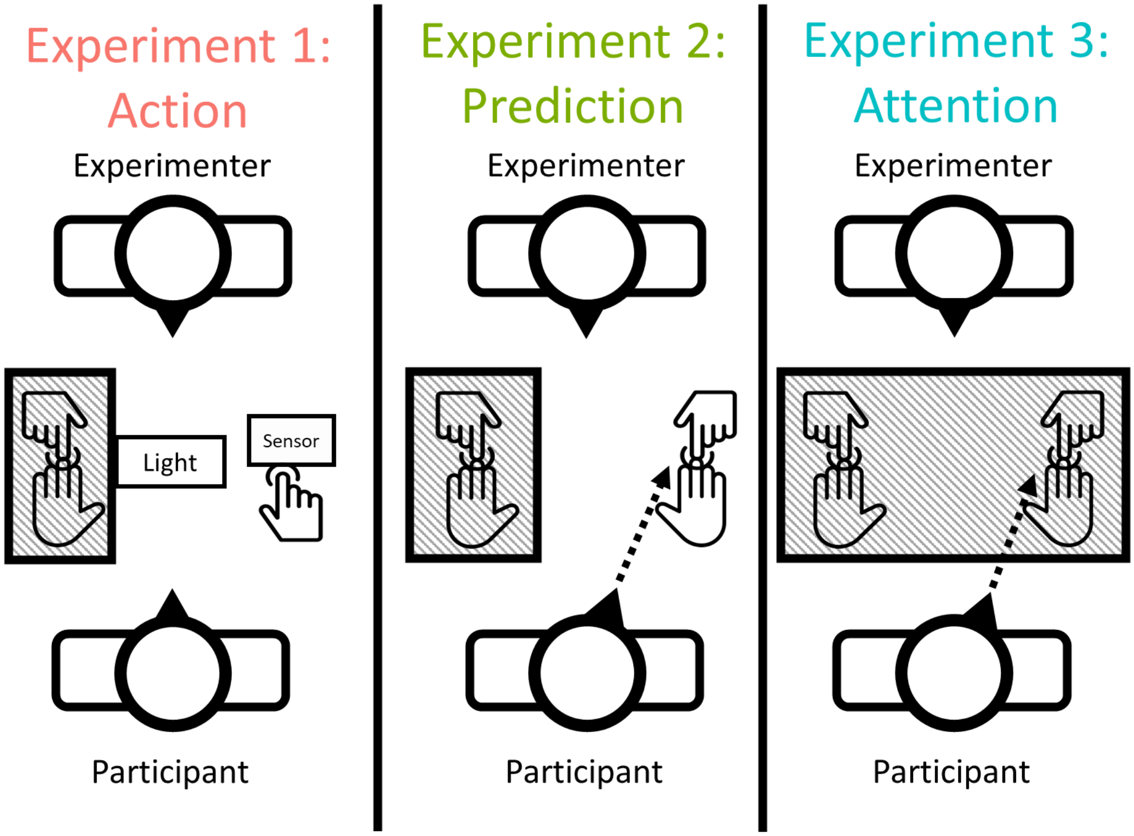

Figure 7. A visual illustration of each experimental condition. In all experiments, the experimenter taps the participants' left hand, which is visually blocked by a physical partition. This functions as a common control between all conditions. In Experiment 1, the participant touches a sensor with their right index finger at the same time the experimenter touches their left index finger. This manipulated stimulus involved participant action. In Experiment 2, the experimenter touches the participant's right index finger at the same time as their left index finger. However, the participant is instructed to look at their right index finger as the touch occurs, allowing them to predict when the manipulated stimulus will happen. In Experiment 3, both hands are visually obscured, but participants are instructed to attend to the manipulated stimulus of their right index finger being touched.

CHAPTER 3

EXPERIMENT 1

METHODS

33 undergraduate ASU student participated in Experiment 1. All participants were over the age of 18, had normal or corrected to normal vision, and normal haptic sensation on both of their hands. Participants sat across a table from the experimenter (Figure 8). For each trial, a light located between the participant and experimenter would flash at random, cuing the participant and experimenter to both tap with their right index fingers. The participant would tap a sensor with their right index finger, while the experimenter would simultaneously tap a sensor on the participant's left index finger. The participant then made a temporal order judgment about which touch happened first. Each participant performed 50 trials. In this experiment, participants judged the time of a touch generated from their own action (manipulated stimulus) and an experimenter's touch (control stimulus). Importantly, the participant could see their own right hand performing the touch, but they could not see the experimenter's hand touching them. One participant was excluded because their accuracy across experiments was less than 50%.

RESULTS

The data were modeled on a group level for the experiment, using a binary logistic regression model. The resultant model contained an intercept coefficient of β_0 = -0.626 and a slope of β_1 = 0.0226. Therefore, the full model is as follows:

$$p(TOJ) = \left(1 + e^{-(-6.26e-1\ +2.25e-2\ *\ time)}\right)^{-1} \quad (3)$$

We replicate the findings of our previous study, showing that participants exhibit a strong ETO Bias. Specifically, we find that when touches are simultaneous, participants report their own touch as having occurred first 65% of the time (y_0 = 0.348, z = -5.06, p < .001).

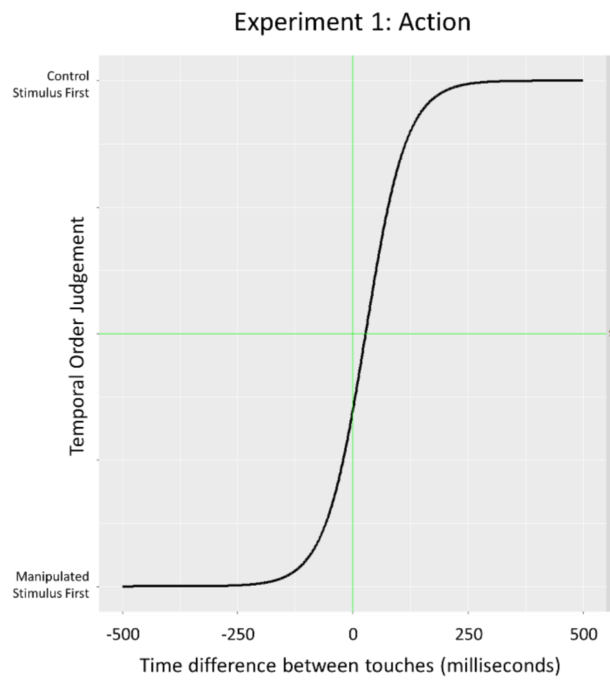

Figure 8. Binary logistic regression model for Experiment 1. The model crosses the y-axis at 0.348, indicating a significant bias for participants to respond that the manipulated stimulus (their own touch) happened first, even when stimuli were simultaneous.

CHAPTER 4

EXPERIMENT 2

METHODS

33 undergraduate ASU students participated in Experiment 2. All participants were over the age of 18, had normal or corrected to normal vision, and normal haptic sensation on both of their hands. Similar to Experiment 1, participants sat across a table from the experimenter (Figure 8). For each trial, the experimenter tapped two sensors on the participants' left and right index fingers, respectively. Participants were then instructed to make a temporal order judgment about which touch happened first. The critical differences between Experiments 1 and 2 are that in Experiment 2, the experimenter performed both touches, removing the action component from the participant in generating one of the two haptic stimuli. Additionally, participants were instructed to look at their right hand. Because visual information was available for one of the stimuli and not the other, participants had differential feed-forward predictability of their right hand being touched (manipulated stimulus) over their left hand being touched (control stimulus). One participant was excluded because their accuracy across experiments was less than 50%.

RESULTS

The data were modeled on a group level for the experiment, using a binary logistic regression model. The resultant model contained an intercept coefficient of β_0 = -0.179 and a slope of β_1 = 0.0193. Therefore, the full model is as follows:

$$p(TOJ) = \left(1 + e^{-(-1.79e-1\ +1.93e-2\ *\ time)}\right)^{-1} \tag{4}$$

Here, we find a significant, albeit diminished, bias for participants to judge the manipulated stimulus as having occurred first. Specifically, we find that when touches are simultaneous, participants report the predictable stimulus having occurred first 55% of the time (y_0 = 0.455, z = -2.64, $p < .01$).

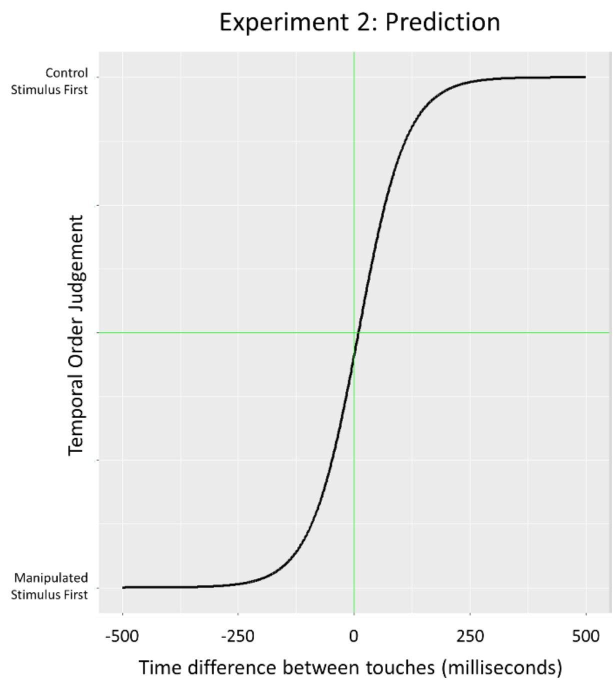

Figure 9. Binary logistic regression model for Experiment 2. The model crosses the y-axis at 0.455, indicating a significant bias for participants to respond that the manipulated stimulus (predictable touch) happened first, even when stimuli were simultaneous.

CHAPTER 5

EXPERIMENT 3

METHODS

33 undergraduate ASU students participated in Experiment 3. All participants were over the age of 18, had normal or corrected to normal vision, and normal haptic sensation on both of their hands. Experiment 3 largely used the same paradigm as Experiment 2 (Figure 8). For each trial, the experimenter tapped two sensors on the participants' left and right index fingers, respectively. Participants were then instructed to make a temporal order judgment about which touch happened first. The critical difference between Experiments 2 and 3 are that in Experiment 3, participants had both of their hands covered. Instead, participants were instructed to look toward their right hand and attend to it. Without differences in action or predictability between the two stimuli, the only difference was differential attention given to their right hand being touched (manipulated stimulus) over their left hand being touched (control stimulus). One participant was excluded because their accuracy across experiments was less than 50%.

RESULTS

The data were modeled on a group level for the experiment, using a binary logistic regression model. The resultant model contained an intercept coefficient of β_0 = -0.00232 and a slope of β_1 = 0.0149. Therefore, the full model is as follows:

$$p(TOJ) = \left(1 + e^{-(-2.32e-3 + 1.49e-2 * time)}\right)^{-1} \quad (5)$$

Here, we find no significant bias for participants to judge either stimulus as having occurred first. Instead, participants are found to respond at chance level when both touches are simultaneous (y_0 = 0.499, z = -0.03, p = n.s.).

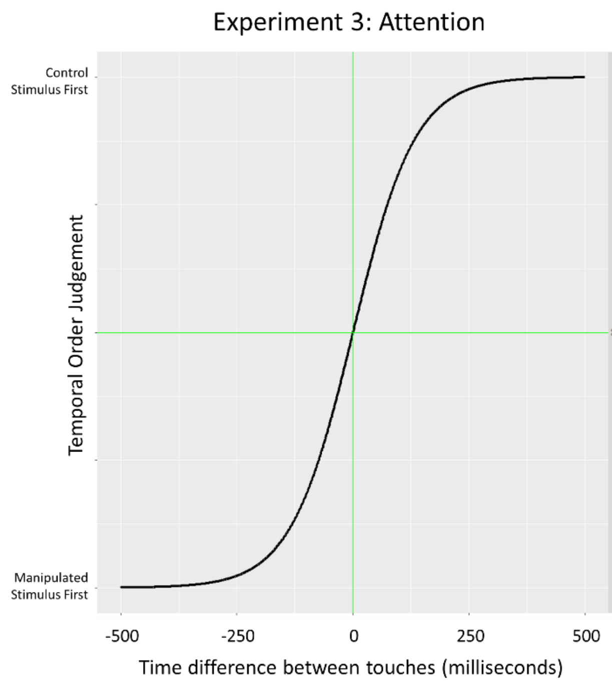

Figure 10. Binary logistic regression model for Experiment 3. The model crosses the y-axis at 0.499, but the value is not statistically significantly different from chance (0.5, indicating equal likelihood to respond either way). This means that when both stimuli were simultaneous, participant responses were statistically random.

CHAPTER 6

DISCUSSION: EXPERIMENTS 1-3

The results from Experiments 1, 2, and 3 demonstrate a bias in both the action and feed-forward predictability experiments. Experiment 1 serves primarily as a replication of previous studies, but also as a baseline comparison for the other two conditions. Because Experiment 1 contains action, stimulus predictability, and attentional focus, it cannot discriminate by itself which mechanisms truly drive the ETO bias.

In Experiment 2, by removing the self-action altogether from the experimental paradigm and comparing a predictable external stimulus to an unpredictable one, we eliminate the possibility of the bias being solely attributable to intentional binding, as intentional binding has been shown to be unaffected by feed-forward predictability of the stimuli (Desantis et al., 2012; Haering & Kiesel, 2014), but requires voluntary action (Cravo, Claessens, & Baldo, 2011). This manipulation demonstrates that predictability contributes to the ETO bias, independent of the participant's voluntary action or intention.

Experiment 3 further removed predictability from the manipulated stimulus, leaving only attentional focus. A bias exhibited in Experiment 3 would indicate a component of the ETO bias completely independent of an internal model or action intention. Instead, we find that the judgments are not statistically different than chance when both touched are simultaneous, indicating no significant effect of attention on participants' temporal order judgments.

In all three experiments, we corrected for biases in mean time difference by factoring it out in the binary logistic regression model. Because mean time differences were linearly correlated with ETO estimates, we wanted to eliminate their effect to see the resultant intercept as a function only of the experimental condition. The reason for the correlation is not empirically confirmed, and both statistical and theoretical explanations may underlie the correlation. For example, if one stimulus is consistently later than the other, temporal binding effects may take place and make them feel experientially simultaneous. This temporal adaptation may result in all judgments being skewed temporally (Bachmann, Põder, & Luiga, 2004; Timm et al., 2014). In addition to theoretical considerations, logistic regression parameters are also sensitive to skewed independent measures, and simply skewing the distribution of stimuli onset differences may result in shifted model parameter estimates (Alkhalaf, 2017).

	Experiment 1	***Experiment 2***	***Experiment 3***
Bias Present	Yes	Yes	No
Action	Yes	No	No
Prediction	Yes	Yes	No
Attention	Yes	Yes	Yes

Table 2. The results from experiments 1-3. Here, we see that a bias is present in both Experiments 1 and 2, but not 3. While action and predictability are both present in Experiment 1, the specific contribution of action cannot be determined because predictability is present in both Experiments 1 and 2. Therefore, it is unknown whether the contributions of action are quantitatively significant.

Importantly, while we demonstrate a bias in Experiment 1, we cannot determine with the current data whether self-action itself is a contributing factor to the ETO bias. This is because feed-forward predictability occurs in both Experiments 1 and 2, and the binary logistic regression models themselves cannot be used to perform Bayesian null-hypothesis testing. In order to further discriminate between the mechanisms of action and prediction, we conducted a fourth experiment, simulating individual regression models to estimate a bias for each participant. By comparing the distributions of these model estimates, we can then evaluate whether the effects seen in Experiments 1 and 2 are quantitatively different.

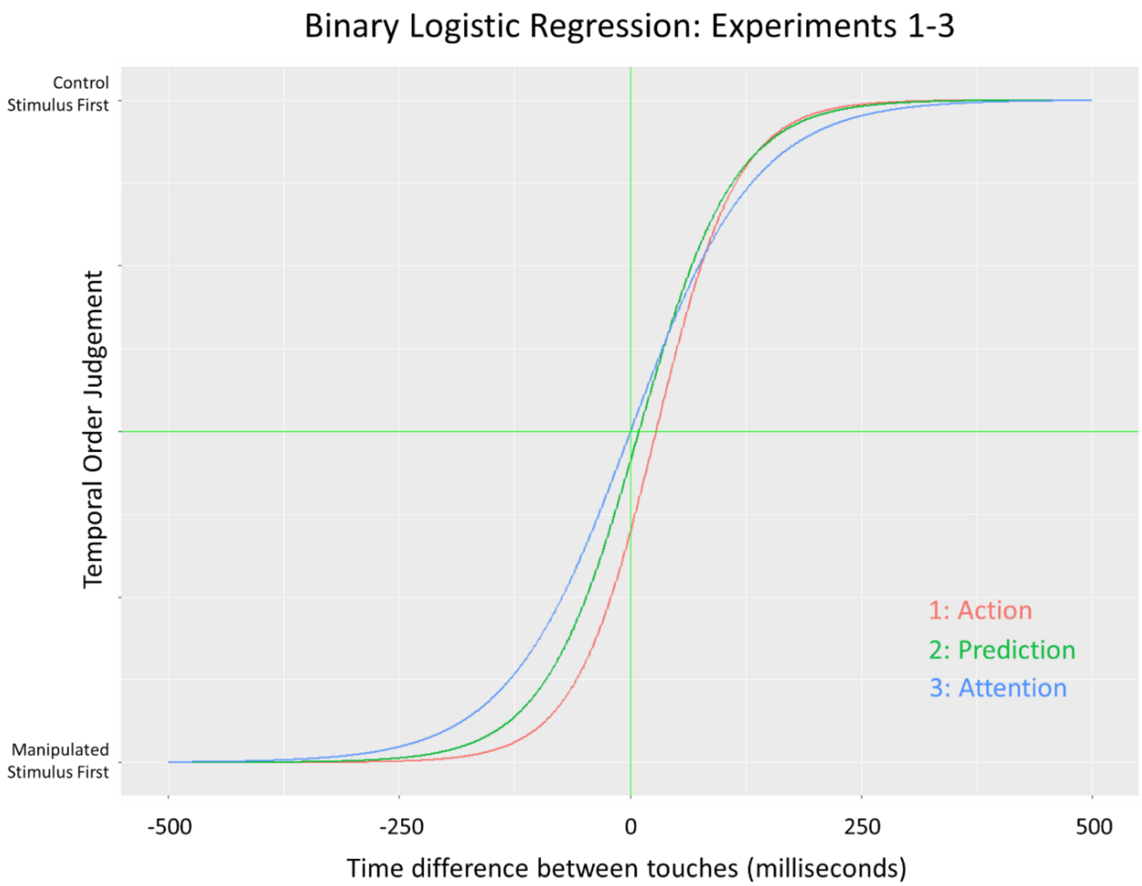

Figure 11. Binary logistic regression models for all three experiments overlaid on a single plot. Both Experiments 1 and 2 had statistically significant y-intercepts, indicating a bias for participants to respond that the manipulated stimulus occurred first when both stimuli were simultaneous. However, no bias was exhibited in Experiment 3.

CHAPTER 7

EXPERIMENT 4

METHODS

In order to avoid biased time differences from the original data while maintaining the stochastic nature, time points were sampled from a Gaussian distribution with a mean of 0 and a standard deviation matching each participant for each experiment. Each data point was then fed as inputs back into the models obtained from the prior experiments in order to obtain probability estimates. These probability estimates were subsequently used to generate a simulated binary temporal order judgment response. This implementation allowed us to sample 50 trials for per participant per experiment, based on the distribution of their own data. This new dataset with a centered x-axis allowed us to generate new models for each participant and create individual bias estimates for each participant in each experiment.

RESULTS

Comparing simulated data from 32 participants across 3 experiments, we replicate the findings from Experiments 1-3. The results from the simulated data of Experiment 1 show a strong bias to report the manipulated stimulus as having occurred first, even when touches are simultaneous ($t(31) = -8.633$, $p < .001$, Cohen’s $d = 1.526$). Additionally, we see the same diminished bias in the simulated data for Experiment 2 ($t(31) = -3.526$, $p < .01$, Cohen’s $d = 0.614$). Finally, the simulated data for Experiment 3 shows no significant bias for participants to respond one way or another when stimuli are simultaneous ($t(31) = 1.772$, p = n.s., Cohen’s $d = 0.313$).

Replicating the findings of our experimental data with simulated data is reassuring. However, our aim with Experiment 4 was to determine whether the results of Experiments 1 and 2 were quantitatively different. In order to do this, we conducted a Bayesian factor analysis to perform null hypothesis testing (Gallistel, 2009; Kwok & Macaluso, 2015; Morey & Rouder, 2011; Rouder, Speckman, Sun, Morey, & Iverson, 2009; Wagenmakers, Wetzels, Borsboom, & Van Der Maas, 2011). By comparing the ratio of the probability of the null model (the bias is statistically indistinguishable between experiments) and an alternative model (that bias is statistically different between experiments) in explaining the data, we attain a Scaled JZS Bayes Factor of 424.5 and a Scaled-Information Bayes Factor of 615.8 (Morey & Rouder, 2011; Rouder et al., 2009). These result indicate that the alternative model is statistically favored, and that the biases exhibited from Experiments 1 and 2 are statistically different. More specifically, this means that the contributions of action and feed-forward predictability in generating the ETO bias are functionally unique. The complete Bayesian analysis results can be found in Table 3.

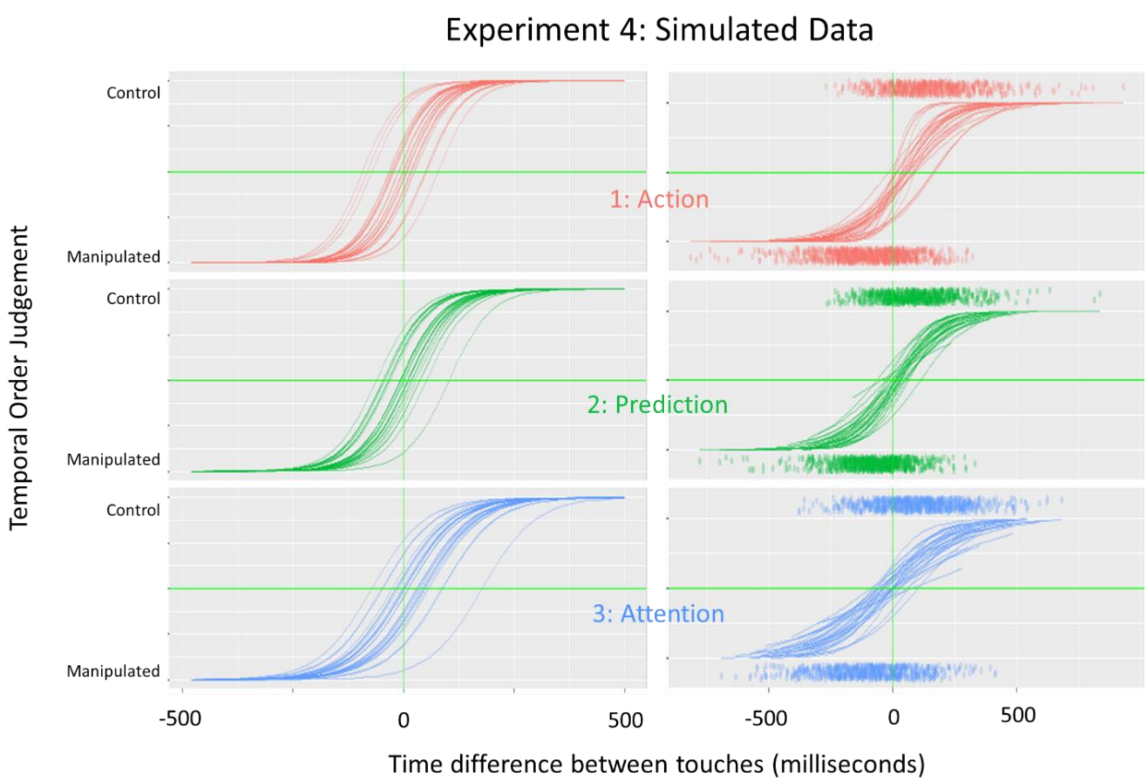

Figure 12. Simulated data for models obtained from Experiments 1-3. Left: regression models estimated for each participant. Right: simulated binary temporal order judgment responses (dots on top and bottom of each graph) and simulated logistic regression models for each participant.

Figure 13. A boxplot of biases attained from the simulated data. Each dot represents the bias of a single participant across each of the 3 Experiments. The findings of Experiments 1-3 are replicated, as significant biases are found for both the Action and Prediction experiments, but not for Attention. Further, a Bayesian factor analysis reveals significant differences between the Action and Prediction experiments.

	Scaled JZS Bayes Factor	Scaled-Information Bayes Factor	Null or Alternative Model Favored
Experiment 1 vs 2 (Action vs Prediction)	4.245 e2	6.168 e2	Alternative
Experiment 1 vs 3 (Action vs Attention)	7.606 e7	1.093 e8	Alternative
Experiment 2 vs 3 (Prediction vs Attention)	2.445 e1	3.331 e1	Alternative

Table 3. Bayesian analysis comparing the results from Experiment 4. In all cases, the alternative model was favored, indicated that the contributions from action, prediction, and attention are all quantitatively unique.

CHAPTER 8

DISCUSSION: EXPERIMENT 4

In Experiment 4, we replicate our experimental findings from Experiments 1-3, and a Bayesian factors analysis reveals that the contributions of action and prediction are unique. While both mechanisms contribute to a bias, we can now conclude that the ETO bias is predominantly driven by action, not feed-forward predictability. We have also demonstrated that within our paradigm, differential attention toward one stimulus over the other is not sufficient to generate a statistically significant bias toward judging one stimulus as having occurred before the other.

CHAPTER 9

CONCLUSION

Previously, it was found that humans exhibit an Egocentric Temporal Order bias when judging the temporal order of their own action-events when compared to simultaneous, externally generated events. The present study replicates the finding of the ETO bias, and investigates the mechanisms driving the bias. Across 4 experiments, we examined whether the bias was driven through action, feed-forward predictability, or differential attentional allocation. Our results robustly show that action and feed-forward predictability result in participants judging one stimulus to occur before another. Additionally, a Bayesian factors analysis reveals that action contributes predominantly to the effect of the ETO bias, above and beyond that of feed-forward predictability. These results contrast with the previous interpretation of the ETO bias, that the phenomena was representative of a feed-forward, predictive model of consciousness (Tang & McBeath, 2019).

The present study represents a leap forward in understanding the ETO bias, and the relationship between action and perception. However, there is still much to be uncovered about the ETO bias. Importantly, the present study does not determine whether the ETO bias reflects a sensory level difference in stimuli processing, if it represents a temporal binding effect such as intentional binding, or if temporal latency is even truly the underlying cause. Indeed, it could still be that the bias in judgment itself is not indicative of a difference in the onset of the stimuli, but rather an artifact of the "expansion" of the duration of the stimulus (Tse, Intriligator, Rivest, & Cavanagh, 2004). This explanation is further supported by findings that longer stimulus duration may result in a later perceived temporal onset (Akyürek & de Jong, 2017).

More broadly, this work contributes to a growing literature on perception-action coupling and subjective time perception, and has larger implications in understanding experiential differences in temporal order. From calling who hit a ball out in a basketball match, to figuring out who stopped first at a stop sign, or why it feels you unfairly lost in a video game, it seems we need to take action to understand why our sense of temporal order may be biased.

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APPENDIX A

IRB APPROVAL

Research involving human subjects conducted under the auspices of Arizona State University is reviewed by the University Human Subjects Institutional Review Board (IRB) in compliance with federal regulations. Research involving human subjects concerns the collection of data on subjects whose performance of any activity is required for the purpose of compiling data. This includes data obtained by observation, interview, questionnaire, experiment, or a secondary source. Documents containing any data collection from human subjects require that applications be submitted to the University Human Subjects IRB for approval before data collection or recruitment of subjects is initiated. For further information, contact the human research coordinator in the Office of Human Research Administration at 480-965-6788 or visit researchintegrity.asu.edu/humans.

This study, STUDY00006929, was approved by IRB coordinator E. Williams of the ASU IRB Office. Both authors have completed Human Research: IRB–Social & Behavioral Research (Group 2) CITI training and hold active certificates.

APPROVAL: EXPEDITED REVIEW

Michael McBeath
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Dear Michael McBeath:

On 10/10/2017 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Effects of Conscious Agency on Temporal Perception.
Investigator:	Michael McBeath
IRB ID:	STUDY00006929
Category of review:	(7)(b) Social science methods, (7)(a) Behavioral research
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• IRB Form, Category: IRB Protocol; • Demographics Questionnaire, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • PSY 320 Recruitment Email, Category: Recruitment Materials; • Consent Form, Category: Consent Form; • PSY 320 Consent Form, Category: Consent Form;

The IRB approved the protocol from 10/10/2017 to 10/9/2018 inclusive. Three weeks before 10/9/2018 you are to submit a completed Continuing Review application and required attachments to request continuing approval or closure.

If continuing review approval is not granted before the expiration date of 10/9/2018 approval of this protocol expires on that date. When consent is appropriate, you must use final, watermarked versions available under the “Documents” tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc: Tim Tang
Victoria Temporini