THE MODULATION OF SENSE OF AGENCY BY OUTCOME DELAY

by

MERVE ERDOGAN

Submitted in partial fulfillment of the requirements for the degree of Master of Arts in Psychology in the Graduate School of Social Sciences and Humanities of Koç University

September, 2021

ACKNOWLEDGEMENTS

I would like to thank my advisor Prof. Fuat Balcı for his support and contribution to my improvement through the program. I find myself rather lucky to work with Prof. Fuat Balcı and to be able to benefit from his knowledge, experience, and maybe most importantly his passion for science. I am almost sure that I could not stay that motivated through the pandemic with all the uncertainty if I did not work with him and see his endless motivation. My deepest hope is to carry all these I learned to the next generation and to be a role model how Prof. Fuat Balcı was for me.

Additionally, I would like to thank the rest of my committee members Asst. Prof. Terry Eskenazi, and Asst. Prof. Hakan Karşılar for their valuable feedback and discussion.

I benefited from and enjoyed the intellectual discussion with Atakan Atamer who also helped the data collection process of some of the experiments. I am glad that I had his friendship and assistance. I also want to thank Tutku Öztel who critically read the drafts many times and gave valuable feedback.

I want to thank TÜBİTAK for their financial support during my graduate study through BİDEB-2210A scholarship.

I cannot express my thanks to Orkun, Naz, Seray, Deniz, and Görkem for all their emotional supports through my master program. They listened to me talking about research ideas and experiments for hours. I am especially thankful to my all friends who participated pilot runs (I know it was not a very pleasant experience).

Last but most importantly, I want to dedicate my thesis to my mother and my favorite person, Şakire. None of these would happen if she was not there for me, all the time even when she was going through hard times. She is the strongest person I have ever met and I hope to have the resilience she has.

Abstract

Sense of agency, the feeling of causing events, depends on the temporal proximity between an action and its outcome. Current study aimed to provide a comprehensive understanding on the modulation of sense of agency by time (i.e., outcome delay). There were three main questions in the present study; a) whether sense of agency modulation by delay depends on the temporal context that the experienced outcome delays constituted b) according to which temporal scale sense of agency is modulated c) whether the implicit and explicit sense of agency presents similar patterns in terms of the effect of outcome delay and its context-dependency. Results showed that a) the effect of outcome delay on agency ratings in a temporal context decreased (a marker of central tendency effect) with experience b) agency judgment was modulated as a function of absolute temporal proximity rather than discriminability between outcome delays suggesting that temporal modulation of sense of agency is not a function of cognitive timing, and c) consistent with the findings in explicit agency judgment, the central tendency was also observed in the implicit sense of agency even though the effect of delay was in the opposite direction compared to explicit sense of agency (increasing effect in the former). These findings shed light on the nature of and the mechanism behind the effect of outcome delay on the different levels of sense of agency.

*Key*words: agency judgment, implicit sense of agency, central tendency, Weber's law

Özet

Eylemlilik hissi kişinin motor hareketlerini kontrol ettiğine ve bunlar ile dış dünyada değişikliklere sebep olduğuna dair farkındalığıdır. Bu çalışma, aksiyon sonuçlarının gecikme ile oluşmasının eylemlilik hissi üzerindeki etkilerini çok yönlü bir şekilde incelemeyi hedeflemiştir. Çalışmada temel olarak üç soru vardır: a) aksiyon ile sonucu arasındaki bir sürenin (aksiyon-sonuç gecikmesi) eylemlilik hissine etkisinin, diğer aksiyon-sonuç gecikmelerinin oluşturduğu zamansal bağlama bağlı olup olmadığı b) hangi zamansal ölçeğe göre eylemlilik hissinin aksiyon-sonuç gecikmesi tarafından şekillendirildiği c) örtük ve açık eylemlilik hislerinin, aksiyon-sonuç gecikmesinin eylemlilik hissi üzerindeki etkisinin zamansal bağlamdan etkilenmesi konusunda benzer sonuçlar sergileyip sergilemediği. Çalışmanın sonuçları gösterdi ki: a) aksiyon-sonuç gecikmesinin eylemlilik hissi derecelendirilmesi üzerindeki etkisi, olası aksiyon-sonuç gecikmelerinin tecrübe edilmesiyle ile azaldı (merkezi eğilim etkisine dair bir gösterge) b) eylemlilik hissi derecelendirilmesi, bilişsel zamanın bir işlevi olarak olarak şekillenmediğine işaret edecek şekilde, aksiyon-sonuç gecikmelerinin birbirleriyle olan göreceli ilişkileri yerine aksiyon ve sonucu arasındaki mutlak zamansal yakınlığa göre module edildi c) açık eylemlilik hissi deneyindeki bulgularla uyumlu olacak şekilde, örtük eylemlilik hissi de merkezi eğilim etkisi gösterdi her ne kadar aksiyon-sonuç gecikmesinin eylemlilik hissi etkisi üzerindeki etkileri bu açık ve örtük eylemlilik hisleri için için zıt yönlerde olsalar da (ilkinde azaltıcı etki). Bu bulgular, aksiyon-sonuç arasındaki zamansal farkın eylemlilik hissinin farklı seviyeleri üzeründeki etkilerinin yapısına ve mekanizmasına belli açılardan ışık tuttu.

Anahtar kelimeler: eylemlilik hissi değerlendirmesi, örtük eylemlilik hissi, merkezi eğilim etkisi, Weber Kanunu

Table of Contents

List of Figures

1. Introduction

In order to infer agency from experiences, individuals need to causally link actions with their outcomes. There are two competing theories on how the temporal proximity between an action and its outcome plays a role in the formation of action-outcome association. On the one hand, a large amount of evidence shows that the feeling of agency over an outcome decreases with its increasing delay since the action (Sato & Yasuda, 2005; Farrer, Valentin, & Hupé, 2013; Wen, Yamashita, & Asama, 2015; Imaizumi & Tanno, 2019). According to this view, there is a certain temporal window for an outcome to be associated with an action (akin to the window of associability in the neurobiology of learning and memory literature - Farrer, Valentin, & Hupé, 2013; Gruber, Fink, & Damm, 1957). The main idea behind this claim is derived from the classical works of Michotte on perceptual causality (Michotte, 1946/1963). In Michotte's studies, a square (A) moves towards another stationary square (B). If the contact time of square A to square B and the onset of B's movement in the same direction as A's movement occurs within a certain temporal window, B's movement is perceived as being caused by A's hitting it. If B starts to move with a delay outside of this temporal window, then the illusionary causality diminishes (Young, Rogers, & Beckmann, 2005; Young & Sutherland, 2009). A similar phenomenon was also observed in the action-outcome association; Individuals feel an illusionary control over outcomes emerging coincidentally with their intentions or actions (Blanco, Matute, & Vadillo, 2013; Matute et al., 2015). Consistently, it was found that the feeling of agency diminishes if the outcome of the action comes with more than two seconds delay - even if the outcome was generated by the participant (Shanks, Pearson, & Dickinson, 1989). Therefore, it was claimed that temporal contugity between an action and its outcome is a necessesary factor for sense of agency emergence.

On the other hand, several lines of evidence challenged this view. For instance, if participants are explicitly informed about the delay between an action and its outcome, this weakens the detrimental effect of delays on the sense of agency (Buehner & May, 2004). Another finding indicated that practicing an action with a constant delay diminishes the necessity of temporal contiguity for the sense of agency to emerge; in fact, participants feel even a higher agency with the experienced delayed outcome than shorter testing (novel) delays (Haering & Kiesel, 2015). Briefly, expectations regarding the outcome delay play a key role in determining the effect of time on sense of agency. Although these studies pointed out the cases in which temporal contiguity may not be required for sense of agency, in these studies the temporal relationship between the action and its outcome was either obvious to the observer (e.g., instructions) or deterministic (e.g., repeatedly experiencing a single delay), which falls short of capturing experiences in the variable temporal contexts of daily life (e.g., variable temporal lags between the action and its outcome).

The Bayesian framework has been successfully applied to such experimental scenarios that more closely approximate the variability in natural settings. The primary function of our perceptual system is making estimations based on limited sensory information in the context of noisy environments. To this end, one computational strategy that the brain uses is cue integration; while the information gathered from one sensory system is not sufficient, it can be supported with other sensory information and/or priors to generate more informed estimates (Trommershäuser, Körding, & Landy, 2012). In the Bayes-optimal integration of cues, the sensory cues are combined based on a weighted average (weighted inversely with their uncertainty - Clark & Yuille, 1990; Knill & Pouget, 2004).). Consequently, observers rely on prior information by depending on the uncertainty in the sensory input (the more uncertain the input, the more reliance on priors.)

The bayesian approach has been also used in the study of the sense of agency. The Cue Integration Theory of Sense of Agency claims that the sense of agency emerges with the integration of internal (i.e., motoric) and external (i.e., sensory) cues as well as priors depending on their reliability (Moore, Wegner, & Haggard, 2009; Synofzik, Vosgerau, & Lindner, 2009; Synofzik, Vosgerau, & Voss, 2013). Furthermore, studies showed that prior thoughts that were generated by subliminal (Jonas et al., 2007) or supraliminal priming (Huys et al., 2020) affect the agency level. Consistent with the weighted average computation, the effect of priming as an external cue was higher when there was no internal cue (action prediction - Moore et al., 2009). Moore & Haggard (2008) found that the sense of agency can be constructed both predictively and postdictively depending on the reliability and availability of the cues. The Bayesian approach also explains the illusions in the sense of agency; when prior thoughts are congruent with the observed action, participants feel as if they are moving the actions of other agents (Wegner, Sparrow, & Winerman, 2004) or magically causing an event (Pronin, Wegner, McCarthy, & Rodriguez, 2006). All these findings support the applicability of the Bayesian approach as an appropriate and normative framework to understand a wide range of phenomena that relate to the sense of agency.

The effect of outcome delay on sense of agency in natural settings (i.e., variable temporal context) also may present a pattern fittingly to the Bayesian framework. When a participant is presented with a stimulus set, “prior knowledge” can be simply replaced by the mean of the stimulus distribution (Jazayeri & Shadlen, 2010). This computational process leads to a robust central tendency phenomenon (Hollingworth, 1910). For instance, short and long durations are overestimated and underestimated, respectively (historically known as Vierordt’s law), which points to the importance of temporal context in time perception (Jazayeri & Shadlen, 2010). Similarly, one would expect that the sense of agency in varying delays presents a central tendency; regressed towards the estimate of agency in the medium delay.

Another important aspect of the dynamics of sense of agency modulation by delay relates to the subjective time scales according to which experienced delays dampen the sense of agency. If sense of agency is modulated by delay as being subject to the representational constraints of cognitive timing, sense of agency over different delays should be affected by the relative discriminability between those delays. In other words, this modulation follows a logarithmic scale and abide by Weber's Law, the hallmark psychophysical property of cognitive timing (Gibbon, 1977). On the other hand, the sense of agency modulation which is mediated by non-cognitive timing would be more likely to follow absolute temporal proximity regardless of a delay's relative discriminability from other delays. To this end, previous studies argued for the role of cognitive timing in the temporal modulation of sense of agency. For instance, Haering and Kiesel (2015) found that participants' judgment of the agency was correlated with the participants' subjective expectancy of the outcome timing based on prior experience. This finding was interpreted as that sense of agency was modulated by perceived time instead of absolute temporal proximity. If the time-dependent modulation of sense of agency depended on the mechanisms of cognitive timing, per related psychophysical relations, one would expect this modulation to stay constant across the levels of a logarithmically spaced delay set.

In the present study we investigated a) whether the effect of a given delay on sense of agency depends on other experienced delays that constitute the temporal context, b) whether the modulation of sense of agency by delays abides with Weber's Law.

2. Experiment 1

2.1. Method

2.1.1. Participants

95 university students participated in the study in return for half-course credit. All participants provided a consent form after they were informed about the procedure. We calculated the mean agency ratings of each participant in each delay for the first half (i.e., block 1) of the trials they rated and the second half (i.e., block 2). Participants whose mean agency ratings were two standard deviations away from the mean of all participants' ratings in any of

the delay ranks in either Block 1 or Block 2 were excluded from the analysis listwise. Consequently, 82 participants (*Female* = 27, *Male* = 55; M_{age} = 19.9, SD_{age} = 1.36) were included in the analysis.

2.1.2. Materials and Procedure

The experiment was created with PsychoPy3 (Peirce et al., 2019) and conducted as an online study (https://pavlovia.org). Participants were informed at the beginning of the experiment as follows "In the experiment, you will be asked to press the spacebar anytime you want in a trial and that pressing the spacebar may result in the presentation of a circle on the screen in some trials. In a proportion of the trials, the circle will be presented by the computer regardless of your response. You will be asked to judge how much you felt your keypress caused the appearance of the circle. If the circle appeared before your keypress, please mark "None" on the scale.". All the instructions were given in Turkish.

As Figure 1 shows, before each trial, an instruction appeared on the screen saying "Please look at the fixation cross until it disappears. You can make a keypress anytime you wish after you see the next instruction saying you can make a keypress". After this instruction, the fixation cross appeared on the center of the screen with a random presentation duration (uniformly distributed between 500ms-1500ms). Following the disappearance of the fixation cross, the instruction saying that anytime the key can be pressed appeared at top of the screen until the agency rating was provided. The keypress did not cause this instruction to disappear to prevent participants from inferring an additional causal relationship with the keypress. After the keypress, a grey circle (with a diameter which was 12% of the screen height) appeared at the screen center for 100 ms after a given delay. To measure the sense of agency, participants were asked to rate the subjective feeling of their action causing the circle to appear on the screen by marking on a continuous slider scale by mouse click (endpoints of slider were marked as "none (1)" and "entirely (9), each integer was marked with a line").

The study had a 3x3 mixed design with delay rank (3 Levels: Short, Medium, Long) as a within-subject factor and mean delay (3 Levels, indicating the different delay sets with varying average delays that the different participant groups were presented) as a between-subject factor. Participants were randomly divided into three delay set groups with different mean delays: *Group 1:* 200ms, 300ms, 450ms; *Group 2:* 300ms, 450ms, 675ms; *Group 3:* 450ms, 675ms, 10125ms.

As depicted in Figure 1 shows, There were two types of trials (test and probe trials). In the test trials, the outcome appeared only contingent on the participants' keypress. In the probe trials, the outcome was set to appear at a certain time after the offset of the fixation cross. If participants made a keypress prior to the outcome's appearance in probe trials, the outcome appeared at one of the delays in the corresponding condition after the participant's keypress. In those cases, the probe trial was set to repeat in the next trial. Therefore, the number of probe trials depended on the response time of the participants in the probe trials. The reason for this adaption was to prevent creating unintended temporal information regarding the action-outcome relationship. In the first probe trial, the outcome was set to appear soon after (i.e., 600 ms) the disappearance of the fixation cross to make sure that every participant saw the outcome to be generated by the computer at least once. In the second probe trial, the outcome was set to appear at a later time point (3.5 seconds) to convey that there is variability in ocurrence times. In the rest of the probe trials, the outcome was set to appear at a random time between 1 - 4.5 seconds (uniformly distributed) after the disappearance of the fixation cross. This interval was decided as an approximate range for the outcome appearing in the test trials considering the keypress times and delays.

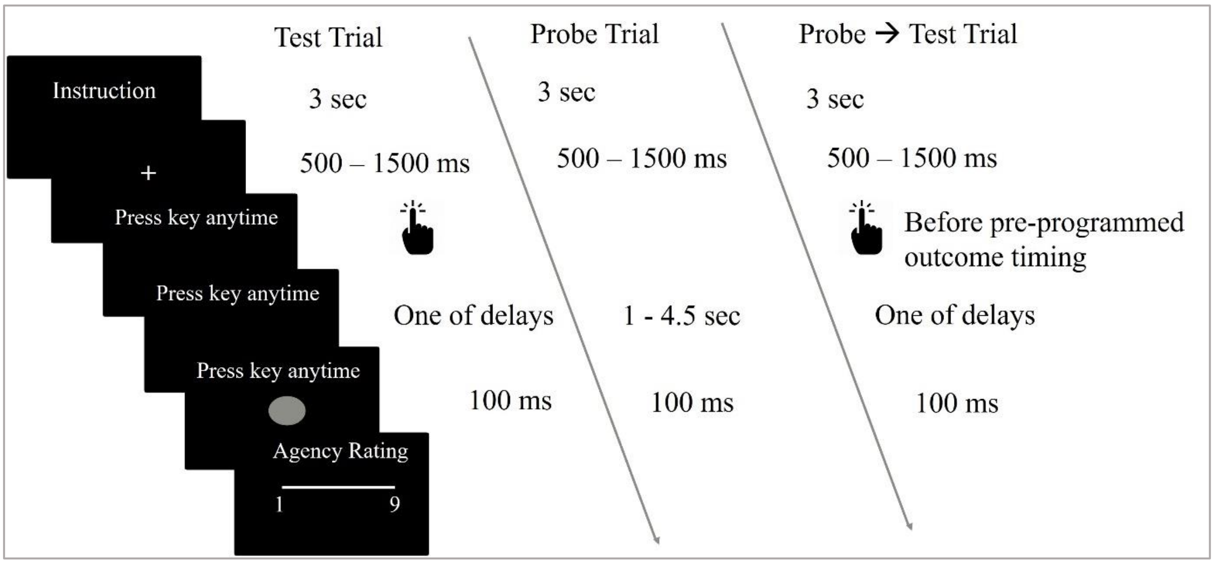

Figure 1. Illustration of the task structure in Experiment 1

Participants were tested over two blocks that contained forty-five trials in each. There were sixty-three test trials distributed evenly among the delay ranks and twenty-seven possible probe trials (the exact number of probe trials varied across participants depending on their keypress times). At the end of all data collection, the trial numbers of short, medium, and long delays were on average 22.5, 22.7, and 22.7, respectively. Detailed reports of trial numbers in the condition levels for each participant can be found in the supplementary material.

2.2. Results and Discussion

When the sphericity assumption was violated in the data, Greenhouse-Geisser correction was reported. Only the trials in which participants made a keypress were included in the analysis. First, the average of the participants' total agency ratings in each delay rank was subjected to a two-way mixed-design ANOVA, with delay rank (3 levels: Short, Medium, Long) as a within-subject factor and mean delay (3 levels: Group 1, Group 2, Group 3) as a between-subject factor to investigate the effect of delay rank on agency judgment. As the visual inspection of Figure 2 suggests, the results showed that delay rank had a significant main effect ($F(1.4, 112.5) = 93.75$, $p < .001$, $\eta_p 2 = .54$); agency ratings decreased with increasing delay rank (all ps < .001 for post hoc comparisons). Consistently, mean delay of the sets had a significant main effect; agency rating decreased with increasing mean delay ($F(2, 79) = 6.21$, $p < .01$, $\eta_p 2 = .13$). These findings support the expected temporal modulation of agency rating based on two different temporal factors.

Furthermore, we compared if the agency rating on average increased with experience. We subjected the average agency ratings of each participant to a two-way ANOVA with block (2 levels: Block 1, Block 2) and mean delay (3 levels: Group1, Group2, Group3). We found that block had a significant main effect on agency ratings ($F(1,79) = 19.07$, $p < .001$, $\eta_p 2 = .19$); agency ratings were higher in Block 2 ($M = 7.53$) than Block 1 ($M = 6.99$). Moreover, there was a significant interaction between block and mean delay ($F(2,79) = 3.98$, $p < .05$, $\eta_p 2 = .09$); the effect of training (i.e., block) on agency rating was higher for the longer mean delays. Therefore, results indicated that the sense of agency increased with practice, which was manifested more strongly for longer delays.

Our main hypothesis was that the experience affects the degree of modulation of agency ratings by outcome delay. To this end, a linear regression analysis was performed for each participant to predict agency judgment based on the delay rank in each block. The slopes of these regressions were operationalized as the agency modulation by delay rank in the corresponding block. We then employed a two-way ANOVA with block (2 levels: Block 1, Block 2) and mean delay (3 levels) using the slope estimates as the dependent variable. As depicted in Figure 2 shows the slope, in other words, the strength of the temporal modulation of sense of agency, was dependent on the block ($F(1,79) = 4.67$, $p < .05$, $\eta_p 2 = .05$); overall, as we expected agency rating was more strongly modulated by delay rank in the first half compared to the second half. This decrease in the strength of the modulation of sense of agency by delay implied that agency ratings regressed towards the rating in the medium delay, in other words, the central tendency effect.

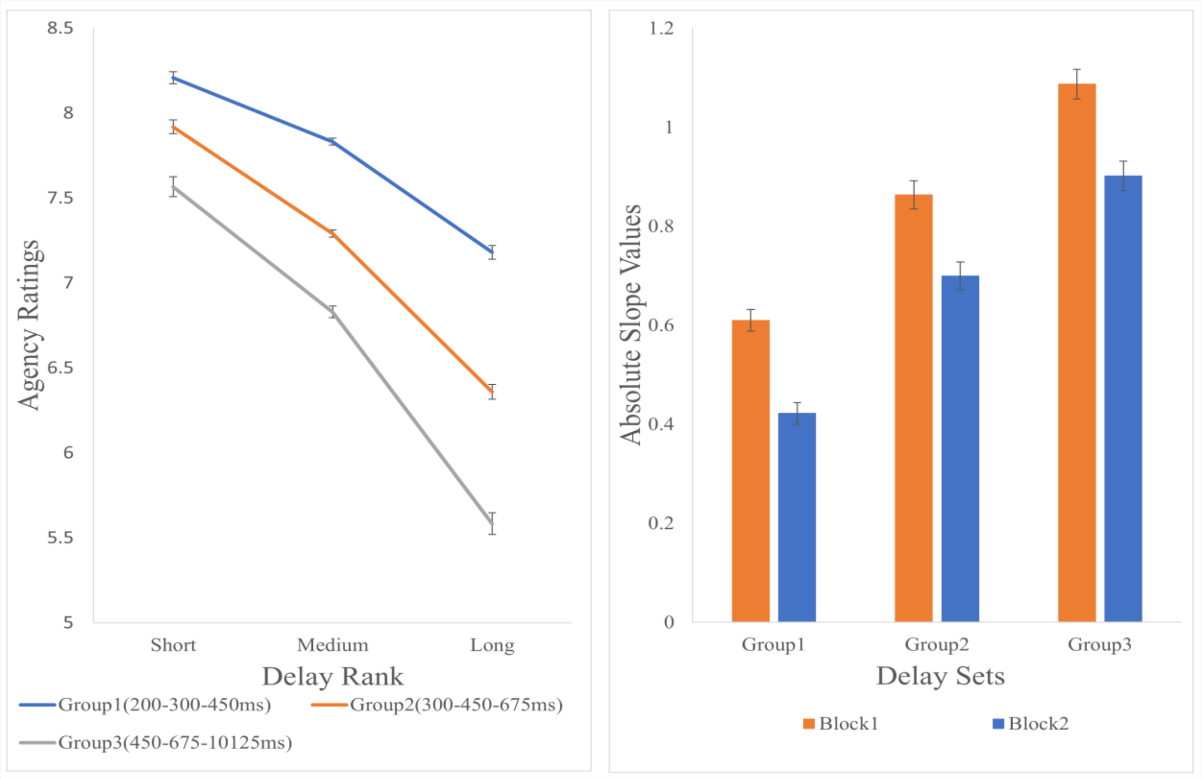

Figure 2. (**Left**) visualizes agency ratings in delay ranks in logarithmically spaced delay sets. (**Right**) visualizes slope values of the regression of agency rating to delay ranks for each block in logarithmically spaced delays. The slope values are normally negative but they are reported as positive for only visualization purposes. Error bars indicate within-subject errors

Importantly, there was a main effect of mean delay on the slope values ($F(2,79) = 3.66$, $p < .05$, $\eta_p 2 = .08$). Increasing mean delay (higher temporal differences between delay ranks in logarithmically spaced delays) led to stronger modulation of agency rating for all the levels of mean delay. Yet, Tukey's post hoc analysis revealed that only the difference between the shortest and the highest mean delay was significant ($t(79) = 2.7$, $p < .05$). This finding pointed out that the sense of agency was modulated by absolute rather than subjective discriminability.

This analysis provided a comparison among agency modulations in the delay sets with different temporal differences yet did not reflect whether the same pattern was observed between the delay ranks in a delay set. The temporal difference between the short and medium delays is lower than the difference between the medium and long delays in logarithmically spaced delay sets. Therefore, if agency modulation by delay was based on absolute temporal differences, the agency judgment should more weakly decrease from the short to the medium delay than the decrease from the medium to the long delay rank. As a complementary analysis, we subtracted the agency ratings of the consecutive delay ranks in each mean delay and ended up with two values; the agency rating difference between the short and medium delay rank conditions (Difference Rank 1) and the rating differences between the medium and long delay rank conditions (Difference Rank 2). Afterward, we employed a two-way ANOVA, with Temporal Difference (2 levels: Difference Rank 1 and Difference Rank 2) as a within-subject factor and mean delay (3 levels: Group1, Group2, Group3) as a between-subject factor. Consistent with the results with mean delay, we found that the temporal difference between the delay rank had a significant effect on the temporal modulation of sense of agency ($F(1,79) = 9.13$, $p < .01$, $\eta_p 2 = .1$); reduction in agency was smaller in short temporal difference ($M = 0.58$, $SE = .08$) than long temporal difference ($M = 0.9$, $SE = .1$). Moreover, Figure 2 shows that agency more strongly decreased in delay sets with higher mean delay ($F(2,79) = 3.79$, $p < .05$, $\eta_p 2 = .08$); supporting the results of regression analysis.

These findings together suggested that sense of agency modulation by delay is based on the absolute temporal proximity rather than the discriminability of delay and does not follow Weber’s law. Then, the modulation of agency should stay constant across linearly spaced delays even though discriminability decreases as delays get longer. In a second experiment we described below we test this hypothesis using linearly spaced delays. We also aimed to replicate the results of Experiment 1 regarding the effect of experience on the temporal modulation of sense of agency with linearly spaced delays.

3. Experiment 2

3.1. Method

3.1.1. Participants

A total of 92 university students participated in the study in return for half-course credit. The data exclusion criteria was the same as Experiment 1. Consequently, 79 participants were included in the analyses (*Female* = 38, *Male* = 36, *Not reported* = 5; M_{age} = 21.3, SD_{age} = 1.38).

3.1.2. Procedure

The same procedure was followed with Experiment 1 except delays. Delays were separated by a constant distance (200ms): *Group 1:* 200ms, 400ms, 600ms; *Group 2:* 400ms, 600ms, 800ms; *Group 3:* 600ms, 800ms, 1000ms.

3.2. Results and Discussion

The exclusion criteria for the trials was the same with Experiment 1. We first checked if we see a similar detrimental effect of delay on agency judgment. We subjected the average agency ratings of each participant to a two-way mixed-design ANOVA, with delay rank as a within-subject factor and mean delay as a between-subject factor to investigate the effect of delay rank on agency judgment. The results showed that both delay rank ($F(1.3, 99.8) = 103.72$, $p < .001$, $\eta_p2 = .57$, all ps < .001 for post hoc comparisons) and mean delay had significant main effects ($F(2, 76) = 4.22$, $p < .05$, $\eta_p2 = .1$); agency rating consistently decreased with increasing delay (Figure 3).

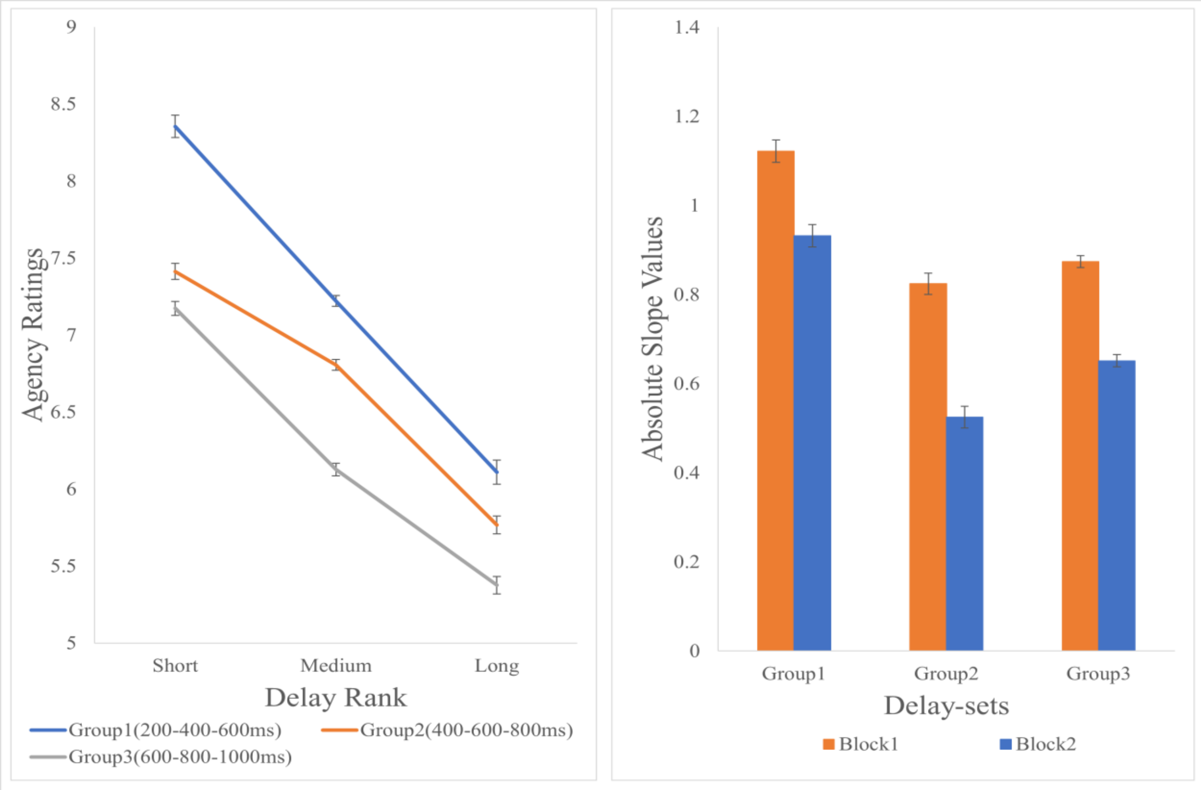

Figure 3. (**Left**) visualizes agency ratings in all delay ranks in linearly spaced delay sets. (**Right**) visualizes absolute slope values of the regression of agency rating to delay ranks for each block in linearly spaced delays. The slope values are normally negative but they are reported as positive for only visualization purposes. Error bars indicate within-subject errors.

Later we investigated whether experience increased agency judgment by comparing the average agency ratings of each participant between blocks. Block had a significant effect on agency ratings ($F(1, 76) = 34.15$, $p < .001$, $\eta_p 2 = .31$); agency ratings was higher in the second half than ($M = 7.22$, $SE = 0.12$) the first half of the experiment ($M = 6.71$, $SE = 0.14$).

More importantly, we investigated whether block had the effect which was observed in Experiment 1 on the temporal modulation of agency rating by delay rank (slope). Similar to the results in Experiment 1, the strength of the temporal modulation of agency was dependent on the block ($F(1,76) = 14.46$, $p < .001$, $\eta_p 2 = .16$); the temporal modulation of agency rating decreased in Block 2 as we expected (Figure 3).

Consistent with the expectations of absolute temporal modulation argument, in contrast to Experiment 1, mean delay did not have a significant main effect on slope values when delays varied linearly ($F(2,76) = 1.96$, $p = .148$) indicating that there was no difference in the strength of temporal modulation across mean delays.

As a follow-up analysis, we investigated whether there was a difference in agency modulation between the consecutive delays. To this end, we employed the same method with Experiment 1; subtracted the agency ratings of the consecutive delay ranks in each mean delay and subjected them to a three-way mixed-design ANOVA, with block and Temporal Difference Rank (2 levels: Difference Rank 1 and Difference Rank 2) as a within-subject factor and mean delay as a between-subject factor. Since temporal differences were constant across delay ranks, we would not see a significant difference in agency modulation between the levels of temporal difference ranks. Supporting this prediction, as it can bee seen in Figure 3, the decrease on the agency rating between the consecutive delays did not differ depending on the delay rank in the linearly spaced sets ($F(1,76) = 1.65$, $p = 0.2$). Together the findings of two experiments suggested that agency modulation was dependent on the absolute temporal proximity instead of the discriminability between the delays.

As these results indicated that temporal modulation of agency judgment and time perception were different in terms of temporal scales used, we investigated whether temporal modulation of agency judgment was also different from time perception in terms of scalar property. Scalar variability as a ubiquitous psychophysical feature of interval timing dictates that standard deviations of temporal judgments increase proportionally with increasing durations (constant coefficient of variation). Thus, we first looked at whether standard deviations of agency ratings were dependent on the delays. We calculated standard deviations (SD) of each participant's agency rating for each delay rank and subjected SD values to a two-way mixed-design ANOVA; delay rank (3 levels: Short, Medium, Long) was a within-subject factor and mean delay (3 levels: Group 1, Group 2, Group 3) was a between-subject factor. In both logarithmically and linearly spaced sets, delay rank had a significant main effect on the SD of agency ratings ($F(2,158) = 34.73$, $p < 0.001$, $\eta_p2 = .3$ and $F(2,152) = 31.38$ $p < .001$, $\eta_p2 = .29$, respectively); SD of agency ratings increased with increasing delay (all ps < .01). Later, we looked at whether SD of agency ratings changed proportionally to delays; we divided SD of agency ratings by the corresponding delay and subjected obtained values to a two-way ANOVA, delay rank as a within-subject factor and mean delay as a between-subject factor. The results of ANOVA showed that in both logarithmically and linearly spaced sets relative variability of agency ratings was dependent on the delay ranks ($F(1.5,122.1) = 10.36$, $p < 0.001$, $\eta_p2 = .11$ and $F(1.4,112.7) = 13.54$ $p < .001$, $\eta_p2 = .15$, respectively); it decreased with increasing delay. Therefore, the variability in agency ratings as a function of delay did not abide by the scalar property.

In both experiments reported above explicit judgments were used for quantifying the sense of agency. But the explicit judgment of sense of agency is susceptible to higher cognitive interference, which decreases the reliability of the related methods of measurement. That has been said, many studies in the literature including the ones investigating the effect of outcome delay used explicit agency judgment as the dependent variable (Haering & Kiesel, 2015; Buehner & May, 2004; Shanks, Pearson, & Dickinson, 1989). Since the present study is an extension of the debate on the effect of temporal contiguity, we found it necessary to use a similar method with previous studies to improve the comparability of the findings. On the other hand, the two-step theory asserts that judgment of agency (JoA) and implicit feeling of agency (FoA) are two distinct constructs (Synofzik, Vosgerau, & Newen, 2008). While JoA is conceptual and higher-order, FoA is low-level and automatic. Studies also found that different brain regions were activated in relation to JoA and FoA (Farrer et al., 2008; Hughes, 2018; Moore, Ruge, Wenke, Rothwell, & Haggard, 2010), and that arousal affects JoA and FoA differently (Wen et al., 2015). Therefore, what we measure in our study does not necessarily generalize to different types of sense of agency and it is possible that agency is differentially modulated by experienced delay in explicit vs. implicit sense of agency. We did not measure explicit and implicit sense of agency together as the paradigm used to measure implicit sense of agency requires the estimation of the delay between the action and the outcome. This may lead participants to make explicit agency judgments depending on the temporal estimation. It may also give participants an idea about the experimenter's demand regarding the relationship between the outcome delay and the agency judgment. In a third experiment, we investigated if the central tendency effect is observed in the implicit sense of agency.

4. Experiment 3

4.1. Method

4.1.1. Participants

100 university students participated in the study in return for half-course credit. Participants whose intentional binding score (the calculation will be explained below) was two standard deviations away from the mean in any of the delay ranks were removed listwise. Consequently, 87 participants were included in the analyses (*Female* = 65, *Male* = 21, *Missing* = 1; M_{age} = 20.9, SD_{age} = 2.87).

4.1.2. Materials and Procedure

Participants were randomly assigned to one of the three delay set conditions with different mean delays. In each delay set, there were three delay ranks. Based on the findings of the previous two experiments, which was that sense of agency was modulated by absolute temporal proximity, we used delays varying with a constant temporal difference; (Group1: 250 – 450 - 650ms, Group1: 250 – 450- 650ms, Group3: 250 – 450- 650ms).

Haggard, Clark, and Kalogera (2002) found that the timings of intentional action and its outcome were perceived as shifted to each other. Since then, this observation, so-called

Intentional Binding, has been used as an implicit marker of the sense of agency (Haggard et al., 2002). The magnitude of this binding has been treated as the magnitude of the sense of agency; stronger binding indicates a higher feeling of agency. One way of measuring intentional binding is asking participants to judge the duration between the action and its outcome which would be shorter for intentional actions than passive observations (Humphreys & Buehner, 2009; Imaizumi & Tanno, 2019; Nolden, Haering, & Kiesel, 2012; Wen et al., 2015). We employed the duration estimation method to measure the implicit sense of agency.

As Figure 4 shows, there were two types of tasks which were presented as blocks: action and baseline. In the action trials, a white colored fixation cross appeared at the center of the black screen; participants were required to press the SPACE key anytime they wished, and the keypress produced a tone (1000Hz, for 100 ms) with varying delays. Fixation cross stayed on the screen for some duration after the tone that was randomly extracted from a uniform distribution (500-800 ms) to prevent the disappearance of fixation cross to be perceived as the outcome of the action. After the disappearance of the fixation cross, in each trial, participants were asked to estimate the duration between their action and the start of the tone as accurately as possible in milliseconds in a slider ranked between 1 – 1200 (ms).

In the baseline trials, instead of making a keypress, participants listened to two tones with the same varying delays as the action trials. First tone (440 Hz) presented at a time which previously was found to approximately corresponds to participants' keypresses (drawn from a uniform distribution 600 - 800 ms) (Imaizumi & Tanno, 2019). The second tone was the same tone used as an outcome in the action trials and followed the first tone with one of the delays. At the end of the trial, participants were asked to estimate the duration between the end of the first tone and the beginning of the second tone as accurately as possible in milliseconds in a slider ranked between 1 – 1200 (ms). This was the most conservative (shortest possible) way for asking the duration in the baseline condition as we expect that the duration in the baseline trials would be estimated longer than the action trials. All delays were presented randomly. Participants completed each block twice. Action and baseline blocks were presented in alternating order but the starting block was counterbalanced (ABAB or BABA). Each block consisted of thirty-nine trials (thirteen for each delay) which makes 156 trials in total.

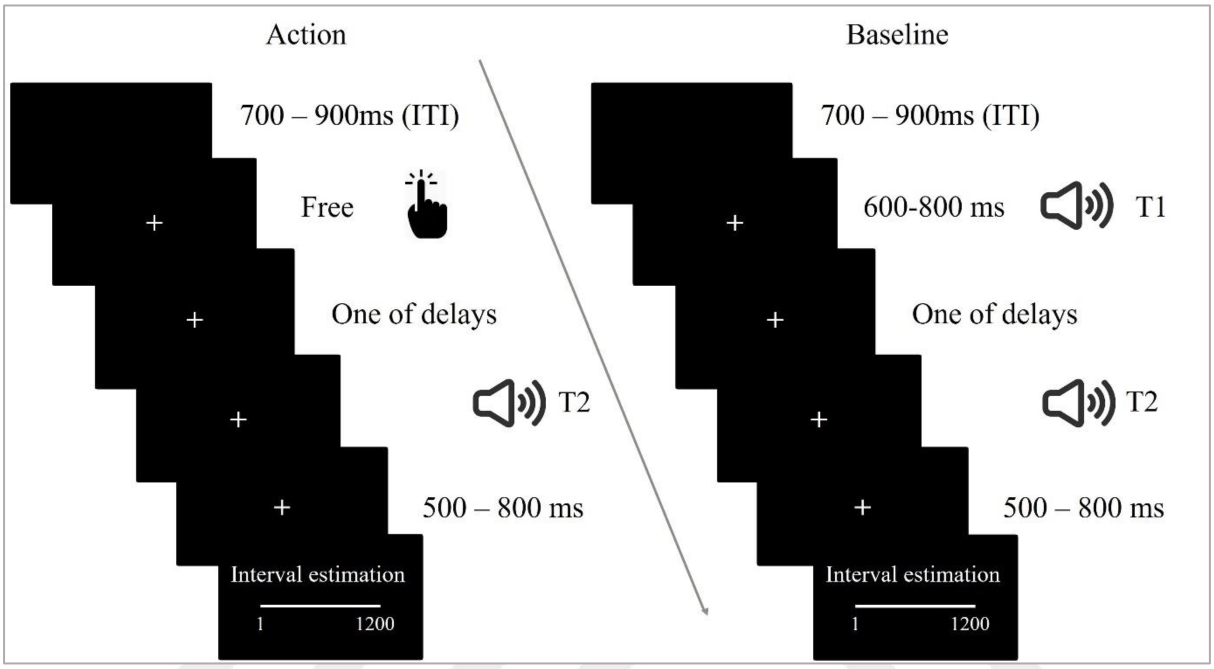

Figure 4. Illustration of the task structure in Experiment 3. Delays were extracted from the same delay set for action and baseline conditions.

4.2. Results

We calculated the mean of the estimated duration in each delay in each task type and subjected the calculated values to a three-way ANOVA with delay-rank (3 levels: Short, Medium, Long) and task (2 levels: action vs baseline) as within-subject factors and mean delay as a between-subject factor (3 levels: Group1, Group2, Group3). Not surprisingly, delay had a significant main effect on estimated durations ($F(1.11, 127.33) = 160.48$, $p < .001$, $\eta_p 2 = .65$); estimated durations increased with delay (all *p*s < .001). Importantly, the task had a significant effect on estimated durations ($F(1,83) = 127.54$, $p < .001$, $\eta_p 2 = .6$); durations were estimated shorter in the action task (*M* = 334, *SE* = 21.9) than baseline task (*M* = 459, *SE* = 23.8), ($t(83) = -11.3$, $p < .001$). Moreover, the differences between the action and baseline conditions were significant in all delay ranks in all mean delay groups (all *p*s < .001) indicating that there was intentional binding for all delays. Also, there was a significant interaction between task type and delay ($F(1.53,127.33) = 44.23$, $p < .001$, $\eta_p2 = .34$); the estimated duration difference between action and baseline tasks increased with increasing delays.

To analyse the degree of this binding effect, we divided the estimated duration in the action condition to the estimated duration in the baseline condition. The obtained value of the proportion was treated as intentional binding value. Lower values of this proportion would mean higher binding and if the proportion was equal to or higher than 1.0 it would indicate that there was no binding. We conducted all analyses of intentional binding with both means and medians of the intentional binding values since most of the values were not normally distributed (see online supplementary material). The results with means and medians were in the same line for all analysis. Therefore, we only reported results gathered based on the means. We first looked at the effect of outcome delay on intentional binding by subjecting average of intentional binding scores (i.e., ratio) to a two-way ANOVA; delay rank (3 Levels: Short, Medium, Long) as a within-subject factor and mean delay (Group1, Group2, Group3) as a between-subject factor. The result revealed that delay rank did not have a significant effect on intentional binding ($F(1.55, 128.83) = 2.23$, $p = .12$). However, there was a significant effect of mean delay ($F(2,83) = 4.45$, $p < .05$, $\eta_p2 = .097$); A post hoc Tukey test showed that; overall, intentional binding decreased with increasing mean delay but only the difference between the shortest mean delay (Group1) and the longest mean delay (Group3) was significant ($t(88) = -2.9$, $p < .05$).

Since we were mainly interested in the effect of experience, we compared the strength of the modulation of intentional binding by delay rank in the first and the second block. Similar to the previous two experiments in this paper, we regressed the average intentional binding to delay ranks for each participant and operationalized the effect of outcome delay on intentional binding as the obtained slope value. The slope values were subjected to a two-way ANOVA with block (2 levels: Block 1, Block 2) as a within-subject factor and mean delay as a between-subject factor. There was a significant effect of block on slope values ($F(1,83) = 7.57$, $p < .01$, $\eta_p 2 = .084$). Tukey's post hoc comparison showed that slope values were significantly lower in Block 1 ($M = -.04$, $SE = .017$) than Block 2 ($M = .009$, $SE = .01$), $t(83) = -2.75$, $p < .01$). The negative slope values indicated that intentional binding increased with delay rank in Block 1. As it can be seen in Figure 5, in Block 2, the slope became nearly zero (decreasing effect of delay rank on intentional binding). One-sample t-test indicated that this value is not significantly different from 0 ($t(86) = 0.75$, $p = .45$). Therefore, the increasing effect of outcome delay on intentional binding which was observed in Block 1 was not significant during Block 2.

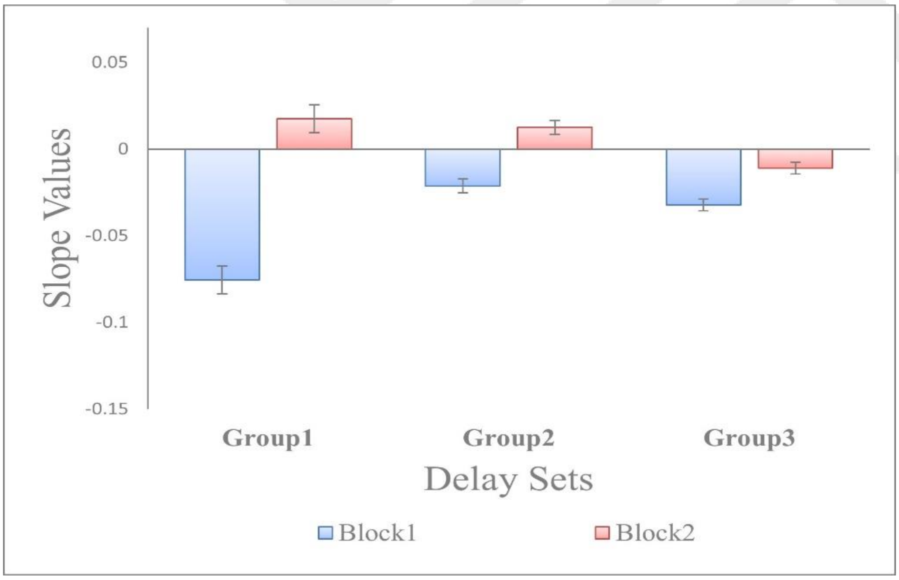

Figure 5. Slope values of the regression of intentional binding to delay ranks for each block in all delay sets.

As a confirmatory analysis, we subjected average intentional binding values to a three-way ANOVA with block and delay rank as within-subject factors and mean delay as a between-subject factor. There was a significant interaction effect between delay rank and block ($F(1.67,138.6) = 5.05$, $p < .05$, $\eta_p 2 = .057$) and there was no significant interaction between delay rank, block and mean delay ($F(3.35,140.6) = 1.17$, $p = .32$). Thus, this result indicated that the effect of delay on intentional binding was different for the first and the second blocks. To elucidate the way of this effect, we conducted two separate ANOVAs with delay rank as a within-subject and mean delay as a between-subject factor for the first and the second block. In the first block, there was a significant effect of delay rank ($F(1.52,127.6) = 4.43$, $p < .05$, $\eta_p2 = .05$); Intentional binding increased with increasing delay. On the other hand, in the second block, the effect of delay rank on intentional binding was not significant ($F(1.81,152.3) = 1.63$, $p = .23$). Therefore, the analyses revealed that the effect of delay on intentional binding was in opposite directions within a delay set and between delay sets. Despite this difference regarding the effect of delay on intentional binding, the effect of delay rank on intentional binding robustly depended on the block.

As a further analysis, we investigated whether sense of agency shortened a specific duration or slowed down the speed of the internal clock. To this end, we employed the same analysis with (Wen et al., 2015). We regressed the estimated interval in action and baseline tasks to delay ranks for each participant. As it was treated in the study of Wen et al. (2015), smaller intercept in the action task would mean shortened duration whereas smaller slope values in the action task would mean slowed internal clock speed. We compared the obtained slopes and intercepts between the task types with two-way ANOVA; task as a within-subject factor and mean delay as a between-subject factor. Results supported both views. Task had a significant main effect in both intercept ($F(1,83) = 8.6$, $p < .01$, $\eta_p2 = .09$) and slope ($F(1,83) = 55.1$, $p < .001$, $\eta_p2 = .39$). Intercept in action task was significantly lower ($M = 158$, $SE = 22.6$) than baseline task ($M = 196$, $SE = 22.5$), ($t(83) = -2.9$, $p < .01$). Slope in action task also was significantly lower ($M = 88.6$, $SE = 8.06$) than the baseline task ($M = 131.6$, $SE = 9.7$), ($t(83) = -7.4$, $p < .001$).

5. General Discussion

In the present study, we investigated the temporal modulation of sense of agency from various angles. Interestingly, the results of Experiment 1 and 2 supported both of the views that the sense of agency over a delayed outcome depends on the temporal context that the other experienced outcome delays constituted of and the temporal contiguity is necessary for sense of agency so that agency judgment decreases with outcome delay. We found that agency judgment decreased with increasing outcome delay as it was previously indicated. However, as the participants experienced the outcome delays, the differences between the agency ratings on the delay ranks decreased and the ratings merged towards their center which was the rating in the medium delay. In other words, the detrimental impact of the outcome delay on the sense of agency decreased with the experience of all outcome delays. On the other hand, the ratings on the center was dependent on the mean delay; on average higher ratings were given in delay sets with shorter durations. These findings together emphasized the importance of both factors on the sense of agency over a delayed outcome (the temporal context that the delay is a part of and the absolute temporal proximity).

One view explains the necessity of temporal contiguity for the causal association between the action and its outcome with limited cognitive resources (Ahn, Kalish, Medin, & Gelman, 1995). According to this account, the longer the outcome delay the longer the events are held in memory. Also, delay decreases the explanatory power of the outcome with the action as the possibility of something else causes the outcome increases in time. Therefore, effects that occur right after the action are easily associated with the action while it is difficult to detect the causal relationship between action and a delayed outcome. This perspective assumes that the judgment of agency over an outcome is primarily stimulus-driven. Nevertheless, it is well-known that perceptual judgments are based on the integration of the current sensory input and past experiences when the sensory input is ambiguous like in the present study. Therefore, agents do not rely solely on stimulus but rather combine the stimulus-driven information with a top-down representation of the related stimulus. Our findings showing that delay had a detrimental impact in Block 1 are in line with the limited cognitive resource view. Yet, we saw that this detrimental effect weakened as participants experienced the outcome delays, thereby they started to combine the stimulus-driven information with the experience of the stimulus set. At the same time, stimulus-driven information has still been a part of the calculation, hence agency judgments were dependent on the mean delay. Therefore, our findings do not necessarily contradict this previously proposed view on temporal contiguity but take it to a further step.

Another effect of experience on agency judgment was that, in both linearly and logarithmically spaced sets, there was an overall increase in agency ratings with experience. Previous findings showing that participants felt higher agency over a practiced delay than shorter testing delays explained the observed phenomenon with the Motor-sensory recalibration (Parsons, Novich, & Eagleman, 2013; Stetson, Cui, Montague, & Eagleman, 2006). The Motor-Sensory recalibration view claims that the time interval between action and repeatedly practiced delay is perceived as shorter. The view explains the functional reason of such recalibration as "... sensory events appearing at a consistent delay after motor actions are interpreted as consequences of those actions, and the brain recalibrates timing judgments to make them consistent with a prior expectation that sensory feedback will follow motor actions without delay." (Stetson et al., 2006). As it can be seen in the quote, this mechanism works in the situation of a constant delay. Nevertheless, our findings showed that the effect of the outcome delay on sense of agency does not decrease only with the repeated practice of a constant delay but the same effect also applies to conditions in which participants experienced a set of delays even after a relatively brief exposure with varying delay which is temporally unpredictable on a trial-to-trial basis. Although strong evidence supports that there is a temporal recalibration over practiced constant delay (Haering & Kiesel, 2015; Stetson et al., 2006; Timm, Schönwiesner, Sanmiguel, & Schröger, 2014), the results of the present study suggest that motor sensory recalibration is not the only mechanism which leads to an increased sense of agency over actions with practiced outcome delay.

Alternatively, the increasing agency ratings we observed in the present study may stem from the experimental design we used. Agency judgment is similar to hypothesis testing. The null hypothesis is that an agent does not cause the outcome, rejection of the null hypothesis implies the sense of agency while retaining implies the opposite. Considering in this framework, overestimation of agency is similar to a type I error which means that agents feel control over events that they did not cause. Underestimation of agency corresponds to a type II error, agents feel as if they did not cause an effect that in fact, they did. Ideally, both of these errors should be avoided. Nevertheless, there are factors that affect which type of error is to be avoided more. If a wrong assumption of agency is more costly, then an agent would tend to underestimate her control over the effect whereas in the case of a higher punishment on missing a causal association of an action and its outcome, it would be the opposite. When both types of error have equal consequences like in the present study, though, agents again tend to overestimate their control over events which is known as the illusion of control in the literature. One well-known example of this phenomenon is that individuals feel as if their picking of a lottery ticket influences their chance of winning (Langer, 1975)Agency ratings in Block 1 determine participants' possible rating range; the average of ratings in the shortest delay corresponds to the highest limit and vice versa. Agency ratings' increasing through the highest limit in the Block 2 can be explained with participants' tendency to overestimate their control over the outcomes over time. In a different experimental setting with punishment for type I errors, we could see a different result in terms of both the rating range and how the ratings change over time. Also, we did not use any novel delay throughout the experiment which we can test if the increase in the agency ratings are specific to the experienced delays or it is an overestimation of agency in general.

The comparison of the first experiments of agency judgment provided information for another fundamental question; the agency judgment modulation by delay depended on absolute instead of the relative relationship between delays. These findings suggest that the temporal relations that underlie sense of agency are not necessarily subject to Weber's law, which would be expected for cognitive timing (Gibbon, 1977). Similar distinctions between action and perception were previously postulated in the vision literature. To this end, Goodale et. al. (2004) dissociated vision-to-act and vision-to-perceive and claimed that these two use different metrics. While vision-to-act relies on absolute metrics, vision-to-perceive relies on relative metrics. Studies supported this distinction by showing that visually guided actions did not present the pattern of Weber's law while visual discrimination did (Ganel, Freud, & Meiran, 2014; Hadad, Avidan, & Ganel, 2012). These findings have been attributed to functional reasons. While visual information used in the action needs to reflect the structure of the real world to be able to act, relative information between the objects is sufficient at the perceptual level. Our finding may imply a similar distinction between temporal information that guides sense of agency processes and explicit temporal judgments. We may speculate that agents need to perceive temporal relationships between actions and their outcomes in an absolute metric to generate causal relationships in the highly dynamic external world. Moreover, the type of action we tested in our experiment is motor actions requiring low-level causal association instead of a higher causal attribution requiring long-term storage of the temporal information. Therefore, different temporal metrics may modulate different types of causal relationships. Future studies need to focus more on the issue of whether there is such a distinction between temporal information processing as it relates to the sense of agency vs. time perception.

An important contribution of the present study is that it provides a comprehensive comparison of the implicit and explicit sense of agency in terms of the modulation of delay. There are numerous studies comparing the implicit and explicit sense of agency from various aspects. One important question is whether these two correlates and measure the same concepts. Our results pointed out discrepancies on how the two constructs are affected by outcome delay. First, contrary to the findings in the agency judgment, the findings of within and between-subject analysis regarding the effect of delay on intentional binding were in different directions. While the average intentional binding was stronger for the delay set with a shorter mean delay, outcome delay had an increasing effect on intentional binding in a delay set. Second, there was no increasing effect of experience on intentional binding in contrast to increased agency ratings with experience. However, the two constructs presented similar patterns in terms of the central tendency effect which was the main comparison point of the present study. We observed that the increasing effect of delay on intentional binding disappeared with experience; intentional bindings regressed towards the mean of all binding values. Therefore, the results of three experiments consistently indicated that the sense of agency modulation by delay can be explained by the Bayesian framework after the temporal context is experienced.

The results of the effect of outcome delay on intentional binding pointing out different directions within and between delay sets may seem contradictory. Yet, this observation actually is another evidence for the effect of temporal context on the modulation of intentional binding by outcome delay. Intentional binding was higher for the longer delay as previously stated. Yet, intentional binding over a certain delay was dependent on the position of this delay among other experienced delays. The common delay among all delay sets (i.e. 450 ms) was the longest delay in the delay set with the shortest mean delay and it was the shortest delay in the delay set with the longest mean delay. The position of the delay of 450 ms among the other delays in a delay set affected intentional binding in 450 ms ($F(2,84) = 5.77$, $p < .01$, $\eta_p 2 = .12$). Tukey's post hoc test showed that intentional binding over actions with the delay of 450 ms was lower when the delay rank of 450 ms was the short delay than both when it was the medium ($t(84) = -2.4$, $p < .05$) and the long delay ($t(84) = -.3.26$, $p < .01$), which again supports the idea that intentional binding increases with delay.

Our results indicated that the delay increased intentional binding yet there are conflicting findings regarding the effect of delay on intentional binding in the literature. Some studies found that intentional binding decreased with outcome delay (Imaizumi & Tanno, 2019; Wen, Yamashita, & Asama, 2015) whereas others found the opposite effect (Ruess, Thomaschke, & Kiesel, 2017). Nevertheless, the theoretical explanations of intentional binding support the notion of the incremental effect of delay on intentional binding. One such theoretical explanation is the internal clock model. According to this model, there is a cognitive clock with a pacemaker-accumulator which emits and counts pulses (Gibbon, Church, & Meck, 1894; Treisman, 1963). It has been proposed that the speed of the pacemaker slows down between action and its outcome which produces and counts fewer pulses, thereby a shorter duration is perceived. Since intentional binding is calculated as the difference between or proportion of the action and baseline conditions, the difference between the accumulated pulses of action and baseline conditions increases with delay. Another theory regarding intentional binding is motor-sensory recalibration. As described earlier, this view claims that the perceived timing of a sensory outcome is shifted back towards the action so that agents feel as if there is no or little delay between action and outcome, and has enhanced the feeling of control. In that case, the longer the outcome delay the longer the shifted duration of the outcome, in other words, temporal binding. Therefore, both of these theoretical accounts support the finding that the difference between (or proportion of) the perceived duration of the action-outcome delay and the perceived duration of two external events increases with the duration.

The current study has a number of limitations. One limitation for the comparison between the implicit and explicit sense of agency was delay durations being different. The reason for starting the delay from 250 ms instead of 200 ms in the implicit sense of agency experiment relies on a previous study which showed that intentional binding increased from 150 to 200 ms whereas it decreased from 200 to 250 ms (Ruess, Thomaschke, & Kiesel, 2017). Ruess et al. (2017) claimed that this discrepancy may stem from distinct mechanisms of intentional binding for the short and long delays. So, we wanted to avoid an additional possible difference between delay ranks.

Second, the action produced different sensory outcomes in our experiments investigating the explicit and implicit sense of agency. Previously it was shown that intentional binding is weaker in visual than auditory outcomes. Since we compared intentional binding between various conditions such as delays, different time points of the experiment, and participants; we preferred a stimulus which we can detect an effect in varying scenarios. However, it is still a question whether and how intentional binding depends on the sensory domain.

The findings of the present study are important for several reasons besides providing a comparison for the explicit and implicit sense of agency. The current study revealed an additional factor (the temporal context that all outcome delays constitute) to the previously shown ones (instruction (Buehner & McGregor, 2006), practice (Haering & Kiesel, 2015), the context of action-outcome (Buehner & May, 2002)) that diminish the effect of outcome delay on agency judgment. More importantly, the temporal context factor applies to the action cases (with varying outcome delays and without any explicit information about the outcome delay) containing more possible occurrences in daily life. Also, the present study provided empirical evidence for the idea that the temporal modulation of both implicit and explicit sense of agency is a result of a computation that is inline with the Bayesian framework. These findings support the idea that there is a shared computational mechanism between different levels of sense of agency.

References

Ahn, W. kyoung, Kalish, C. W., Medin, D. L., & Gelman, S. A. (1995). The role of covariation versus mechanism information in causal attribution. *Cognition*, 54(3), 299-352. https://doi.org/10.1016/0010-0277(94)00640-7

Blanco, F., Matute, H., & Vadillo, M. A. (2013). Interactive effects of the probability of the cue and the probability of the outcome on the overestimation of null contingency. *Learning and Behavior*, *41*, 333-340. https://doi.org/10.3758/s13420-013-0108-8

Buehner, M. J., & May, J. (2002). Knowledge mediates the timeframe of covariation assessment in human causal induction. *Thinking and Reasoning*, *8*(4), 269-295. https://doi.org/10.1080/13546780244000060

Buehner, M. J., & May, J. (2004). Abolishing the effect of reinforcement delay on human causal learning. *Quarterly Journal of Experimental Psychology Section B: Comparative and Physiological Psychology*, *57*(2b), 179-191. https://doi.org/10.1080/02724990344000123

Clark, J. J., & Yuille, A. L. (1990). *Data Fusion for Sensory Information Processing Systems*. Boston: Springer, Boston, MA. https://doi.org/10.1007/978-1-4757-2076-1

Farrer, C., Valentin G., Hupé, J. M. (2013). The time windows of the sense of agency. *Consciousness and Cognition*, *22*(4), 1431–1441. https://doi.org/10.1016/j.concog.2013.09.010

Farrer, C., Frey, S. H., Van Horn, J. D., Tunik, E., Turk, D., Inati, S., & Grafton, S. T. (2008). The angular gyrus computes action awareness representations. *Cerebral Cortex*, *18*(2), 254–261. https://doi.org/10.1093/cercor/bhm050

Ganel, T., Freud, E., & Meiran, N. (2014). Action is immune to the effects of Weber's law throughout the entire grasping trajectory. *Journal of Vision*, *14*(7), 1-11. https://doi.org/10.1167/14.7.11

Gibbon, J., Church, R. M., & Meck, W. H. (1894). Scalar timing in memory 1984. *Annals of the New York Academy of Sciences, 423,* 52-77.

Gibbon, John. (1977). Scalar expectancy theory and Weber's law in animal timing. *Psychological Review*, *84*(3), 279–325. https://doi.org/10.1037/0033-295X.84.3.279

Goodale, M. A., Westwood, D. A., & Milner, A. D. (2004). Two distinct modes of control for object-directed action. In H. S. Sharma & A. Sharma (Eds.). *Progress in Brain Research: Nanomedicine and Neuroprotection in Brain Diseases, 144* (pp. 131-144). InTech. https://doi.org/10.1016/S0079-6123(03)14409-3

Gruber, H. E., Fink, C. D., & Damm, V. (1957). Effects of experience on perception of causality. *Journal of Experimental Psychology*, *53*(2), 89–93. https://doi.org/10.1037/h0048506

Hadad, B. S., Avidan, G., & Ganel, T. (2012). Functional dissociation between perception and action is evident early in life. *Developmental Science, 15*(5), 653-658. https://doi.org/10.1111/j.1467-7687.2012.01165.x

Haering, C., & Kiesel, A. (2015). Was it me when it happened too early? Experience of delayed effects shapes sense of agency. *Cognition, 136,* 38-42. https://doi.org/10.1016/j.cognition.2014.11.012

Haggard, P., Clark, S., & Kalogeras, J. (2002). Voluntary action and conscious awareness. *Nature Neuroscience,* 5, 382–385. https://doi.org/10.1038/nn827

Hollingworth, H. L. (1910). The Central Tendency of Judgment. *The Journal of Philosophy, Psychology and Scientific Methods, 7(*17), 461-469. https://doi.org/10.2307/2012819

Hughes, G. (2018). The role of the temporoparietal junction in implicit and explicit sense of agency. *Neuropsychologia*, *113*, 1–5. https://doi.org/10.1016/j.neuropsychologia.2018.03.020

Humphreys, G. R., & Buehner, M. J. (2009). Magnitude Estimation Reveals Temporal Binding at Super-Second Intervals. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(5), 1542–1549. https://doi.org/10.1037/a0014492

Huys, A. C. M. L., Edwards, M. J., Bhatia, K. P., & Haggard, P. (2020). Modulation of Reaction Times and Sense of Agency via Subliminal Priming in Functional Movement Disorders. *Frontiers in Neurology, 11,* 1-8. https://doi.org/10.3389/fneur.2020.00989

Imaizumi, S., & Tanno, Y. (2019). Intentional binding coincides with explicit sense of agency. *Consciousness and Cognition*, *67*, 1–15. https://doi.org/10.1016/j.concog.2018.11.005

Jazayeri, M., & Shadlen, M. N. (2010). Temporal context calibrates interval timing. *Nature Neuroscience*, 13, 1020–1026. https://doi.org/10.1038/nn.2590

Jonas, M., Biermann-Ruben, K., Kessler, K., Lange, R., Bäumer, T., Siebner, H. R., … Münchau, A. (2007). Observation of a finger or an object movement primes imitative responses differentially. *Experimental Brain Research*, *177*, 255-265. https://doi.org/10.1007/s00221-006-0660-y

Knill, D. C., & Pouget, A. (2004). The Bayesian brain: The role of uncertainty in neural coding and computation. *Trends in Neurosciences, 27(*12), 712-719. https://doi.org/10.1016/j.tins.2004.10.007

Körding, K. P., & Wolpert, D. M. (2004). Bayesian integration in sensorimotor learning. *Nature, 427*, 244-247. https://doi.org/10.1038/nature02169

Langer, E. J. (1975). The illusion of control. *Journal of Personality and Social Psychology*. *32*(2), 311–328, https://doi.org/10.1037//0022-3514.32.2.311

Matute, H., Blanco, F., Yarritu, I., Díaz-Lago, M., Vadillo, M. A., & Barberia, I. (2015). Illusions of causality: How they bias our everyday thinking and how they could be reduced. *Frontiers in Psychology*, *6*, 888. https://doi.org/10.3389/fpsyg.2015.00888

Moore, J., & Haggard, P. (2008). Awareness of action: Inference and prediction. *Consciousness and Cognition, 17*(1), 136-144. https://doi.org/10.1016/j.concog.2006.12.004

Moore, J. W., Ruge, D., Wenke, D., Rothwell, J., & Haggard, P. (2010). Disrupting the experience of control in the human brain: Pre-supplementary motor area contributes to the sense of agency. *Proceedings of the Royal Society B: Biological Science*, 277(1693). https://doi.org/10.1098/rspb.2010.0404

Moore, J. W., Wegner, D. M., & Haggard, P. (2009). Modulating the sense of agency with external cues. *Consciousness and Cognition, 18*(4), 1056-1064. https://doi.org/10.1016/j.concog.2009.05.004

Nolden, S., Haering, C., & Kiesel, A. (2012). Assessing intentional binding with the method of constant stimuli. *Consciousness and Cognition, 21*(3), 1176-1185. https://doi.org/10.1016/j.concog.2012.05.003

Parsons, B. D., Novich, S. D., & Eagleman, D. M. (2013). Motor-sensory recalibration modulates perceived simultaneity of cross-modal events at different distances. *Frontiers in Psychology*, *4*, 46.

Peirce, J. W., Gray, J. R., Simpson, S., MacAskill, M. R., Höchenberger, R., Sogo, H., Kastman, E., Lindeløv, J. (2019). PsychoPy2: experiments in behavior made easy. *Behavior Research Methods.*

Pronin, E., Wegner, D. M., McCarthy, K., & Rodriguez, S. (2006). Everyday magical powers: The role of apparent mental causation in the overestimation of personal influence. *Journal of Personality and Social Psychology, 91*(2), 218–231. https://doi.org/10.1037/0022-3514.91.2.218

Ruess, M., Thomaschke, R., & Kiesel, A. (2017). The time course of intentional binding. *Attention, Perception, and Psychophysics, 79***,** 1123–1131 . https://doi.org/10.3758/s13414-017-1292-y

Sato, A., & Yasuda, A. (2005). Illusion of sense of self-agency: Discrepancy between the predicted and actual sensory consequences of actions modulates the sense of self-agency, but not the sense of self-ownership. *Cognition, 94*(3), 241-255. https://doi.org/10.1016/j.cognition.2004.04.003

Shanks, D. R., Pearson, S. M., & Dickinson, A. (1989). Temporal Contiguity and the Judgement of Causality by Human Subjects. *The Quarterly Journal of Experimental Psychology Section B, 41*(2b). https://doi.org/10.1080/14640748908401189

Stetson, C., Cui, X., Montague, P. R., & Eagleman, D. M. (2006). Motor-Sensory Recalibration Leads to an Illusory Reversal of Action and Sensation. *Neuron, 51,* 651–659 https://doi.org/10.1016/j.neuron.2006.08.006

Synofzik, M., Vosgerau, G., & Lindner, A. (2009). Me or not me - An optimal integration of agency cues? *Consciousness and Cognition*, *18*(4), 1065-1068. https://doi.org/10.1016/j.concog.2009.07.007

Synofzik, M., Vosgerau, G., & Newen, A. (2008). Beyond the comparator model: A multifactorial two-step account of agency. *Consciousness and Cognition, 18*(4), 1065-1068. https://doi.org/10.1016/j.concog.2007.03.010

Synofzik, M., Vosgerau, G., & Voss, M. (2013). The experience of agency: An interplay between prediction and postdiction. *Frontiers in Psychology*, *4*(127), 1-6. https://doi.org/10.3389/fpsyg.2013.00127

Timm, J., Schönwiesner, M., Sanmiguel, I., & Schröger, E. (2014). Sensation of agency and perception of temporal order. *Consciousness and Cognition*, *23*, 42–52. https://doi.org/10.1016/j.concog.2013.11.002

Treisman, M. (1963). Temporal discrimination and the indifference interval. Implications for a model of the “internal clock”. *Psychological Monographs*, 77(13), 1–31. https://doi.org/10.1037/h0093864

Trommershäuser, J., Körding, K. P., & Landy, M. S. (2012). *Sensory Cue Integration*. Oxford Scholarship Online. https://doi.org/10.1093/acprof:oso/9780195387247.001.0001

Wegner, D. M., Sparrow, B., & Winerman, L. (2004). Vicarious agency: Experiencing control over the movements of others. *Journal of Personality and Social Psychology, 86*(6), 838–848.. https://doi.org/10.1037/0022-3514.86.6.838

Wen, W., Yamashita, A., & Asama, H. (2015). The influence of action-outcome delay and arousal on sense of agency and intentional binding effect. *Consciousness and Cognition, 36*, 87-95. https://doi.org/10.1016/j.concog.2015.06.004

Yoshie, M., & Haggard, P. (2013). Negative emotional outcomes attenuate sense of agency over voluntary actions. *Current Biology*, *23*(20), 2028–2032. https://doi.org/10.1016/j.cub.2013.08.034

Young, M. E., Rogers, E. T., & Beckmann, J. S. (2005). Causal impressions: Predicting when, not just whether. *Memory and Cognition*, *33*, 320–331. https://doi.org/10.3758/BF03195320

Young, M. E., & Sutherland, S. (2009). The spatiotemporal distinctiveness of direct causation. *Psychonomic Bulletin and Review*, *16*, 729–735. https://doi.org/10.3758/PBR.16.4.729

Supplementary Material

1. Experiment 1

Table S1.

Trial numbers of each delay ranks of each participants

Short	Medium	Long
20	24	22
21	22	23
23	20	23
22	23	22
21	21	25
22	24	22
27	24	24
18	26	27
24	22	25
22	21	23
23	23	20
21	24	21
23	22	21
21	24	22
23	22	21
24	24	20
21	23	22
26	26	24
27	29	24
24	24	24
23	22	22
26	27	27
24	24	25
24	22	21
24	21	21
22	22	22
21	22	23
22	24	25
21	22	23
26	24	26
26	30	26
20	22	24
24	21	21
27	27	27
22	23	22

23	20	23
22	21	23
22	22	24
21	24	22
23	25	24
22	23	21
22	22	22
23	20	23
26	29	25
22	22	23
24	22	21
24	24	25
23	22	21
22	22	22
24	18	24
23	24	24
22	22	22
27	26	26
22	22	22
24	21	22
22	22	22
21	21	24
24	22	20
21	21	24
27	21	25
22	23	21
23	20	23
23	22	21
24	19	26
22	23	21
23	22	21
25	21	23
21	23	22
19	22	25
22	24	20
26	24	24
23	21	22
23	23	21
26	27	24
27	25	28
22	23	21
22	22	22
20	24	22
20	27	26
25	20	24
23	20	23

27	25	25

2. Experiment 3

Table S2

Percentage of non-normal distrubitons of intentional bindings in each delay rank of each block

Block 1			Block 2		
Short	**Medium**	**Long**	**Short**	**Medium**	**Long**
0.7352941	0.5294118	0.3529412	0.5882353	0.3529412	0.4411765
0.5714286	0.3714286	0.3142857	0.4	0.2857143	0.2571429
0.5714286	0.4	0.3428571	0.4285714	0.3142857	0.4571429