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Time perception and the experience of agency

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Abstract

In the current study, we investigate whether sense of agency over an effect coincides with the perceived time of the effect that occurs either at its usual time or earlier or later than usual. One group of participants usually perceived an action effect immediately after the action, another group delayed by 250 ms. In test blocks the effect stimulus was sometimes presented earlier or later than usual. Participants judged either the degree of experienced agency over the effect or whether the effect had appeared at its usual time, or earlier or later than usual. In both groups experienced agency and the perception of the effect's time 'as usual' were highly correlated. To rule out that time judgments influenced sense of agency, we replicated the pattern of agency judgments in Experiment 2 in which participants only judged agency. Taken together, we demonstrated that agency and time judgments vary similarly across temporal deviations of effects irrespective of to which delay participants were adapted to. The high correlation of judgment types indicates that perceiving an effect at its usual time and sensing to have caused the effect are closely related. In contrast, physical temporal proximity of actions and effects has only a minor impact on experienced agency.

204 words

Keywords: Time perception, sense of agency, causality perception, intentional binding

Successful interaction with our environment requires sensing which changes in the environment are self-produced and which are caused by other sources. Only when we realize which environmental changes are caused by our actions and which ones occur independent of us, we can learn causal action-effect relations enabling us to actively manipulate our environment and to choose actions suited to produce intended effects (e.g., Dickinson, Shanks, & Evenden, 1984; Herbart, 1825; Hoffmann et al., 2007; Hommel, 2003; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Kiesel & Hoffmann, 2004; Pfister, Kiesel, & Melcher, 2010).

Whether we sense that an environmental change occurs because of an own action or whether we ascribe it to another cause depends on temporal contiguity. A recent study of Greville & Buehner (2010), for example, demonstrated that the sense of agency, i.e. the feeling to have caused an effect, depends on the contingency between action and effect as well as on the temporal contiguity between action and effect. Likewise Metcalfe, Eich & Castel (2010) observed reduced judgments of agency if an action produced delayed rather than immediate effects.

These recent studies fit nicely to the classical consideration of Hume (1739) who postulated that temporal contiguity fosters the perception of two events to be causally related and to classical studies of Michotte (1946/1963) on causality perception. In Michotte's experiments, the movements of two objects were judged as causally related when the first object hit a second one, stopped, and the second started moving immediately or with a delay of up to 42 ms (Michotte, 1946/1963). The larger the delay between the first and second movement, the less participants judged the movements as causally related, and movements delayed by 140 ms or more were judged predominantly as independent from each other. Thus, in absence of any other information or further knowledge, two events (and with that actions and effects) are perceived the more causally related the closer they occur in time (see also for example Choi & Scholl, 2006; Grassi & Casco, 2009; Lagnado & Sloman, 2006).

Similarly, temporal delays between action and effect impact on the acquisition of action-effect relations. If, for example, an effect always occurs delayed after an action, the acquisition of the action-effect relation is impeded (e.g., Elsner & Hommel, 2004). Likewise, operant conditioning is hindered, if reward (a positive effect) occurs delayed after the operant behavior. Only if there is an immediate intermediate effect, as for example a light that is switched on because of the operant behavior, action-effect (reward) learning occurs unhindered for delayed reward (Lattal, 1984; see also Lattal, 2010 for a recent overview on delayed reinforcement).

However, there are also examples, when delays between an action and its effect do not reduce the sensation that an action caused an effect. In a study of Buehner & McGregor (2006), participants first learned that a marble put onto a Bernoulli board turned on a light when it reached the floor. The slant of the board was either low or high and consequently the marble reached the floor either slow or fast. Then participants observed the experimenter putting a marble into the now covered Bernoulli board and the light turned on after a short or a long delay. Participants were informed that the light could now be caused either by the marble or by a computer and they were asked to judge the extent to which the marble had caused the light. With low slant participants judged the light to be caused by the marble to a higher degree when it brightened up after the long rather than the short delay. Thus, if participants were informed explicitly that an action produced a delayed effect, the delay between action and effect did not reduce the feeling of participants that the action caused the effect (see also Buehner & May, 2002; 2004 for similar results).

In addition, there are some demonstrations that a delay between an action and an effect did not reduce the sense of agency when persons repeatedly experienced that an action effect occurred delayed. Buehner & May (2003), for example, asked participants to judge whether a key press produced a visual effect. The action produced the effect in 75% and, crucially, the effect occurred immediately after the action in some blocks and delayed in others. Half of the participants were informed that there could be a delay while the other half was not informed about a possible delay. For uninformed participants, the order of conditions mattered. When they experienced the delayed condition first they rated the effectiveness to cause the effect higher than when they experienced the immediate condition first. Thus, past experience of delayed or immediate effects altered the feeling of control over delayed effects.

Comparable results emerge regarding the acquisition of action-effect relations. Recently, we demonstrated that participants learn that actions produce delayed effects (Haering & Kiesel, 2012, see also Cunningham, Billock, and Tsou, 2001). For example, a left key press resulted in an effect after a short delay and a right key press resulted in another effect after a long delay. To assess whether participants acquired these action-effect interval relations, they had to respond to the effects. Participants responded faster to effects occurring after their usual delay compared to unexpected early effects demonstrating that they were able to learn that an action produced an effect after a specific delay.

Taken together, delays between actions and effects reduce the impression of having caused the effect and they impede action-effect learning. However, temporal delays between actions and effects can be instructed or learned so that the effect is expected after a specific delay and agency judgments are not necessarily reduced (or are even increased) for delayed effects.

Interestingly another line of research shows that time perception is altered if actions produce effects after delays. A number of studies demonstrated that the time point of actions and effects are perceived closer in time than they actually are (Cravo, Claessen, & Baldo, 2011; Haggard, Clark & Kalogeras, 2002; Haggard & Cole, 2007; Moore & Haggard, 2008; Moore, Lagnado, Deal, & Haggard, 2009; Wohlschläger, Engbert, & Haggard, 2003; Wohlschläger, Haggard, Gesierich, & Prinz, 2003) or that the interval between action and effect is perceived shorter than it actually is (Engbert, Wohlschläger, Thomas, & Haggard, 2007; Nolden, Haering, & Kiesel, 2012; Wenke & Haggard, 2009).

This bias in time perception can even influence the perceived order of action and effects. In a study of Stetson, Cui, Montague & Eagleman (2006), participants repeatedly experienced a tone effect 100 ms after a key press in an adaptation phase. In a test phase the same tone occurred at variable delays shortly before or after the action. Participants' task was to judge whether the tone occurred before or after the key press. When participants had experienced a delay of 100 ms between key press and tone in the block before, they perceived the majority of tones up to 64 ms after the key press as having occurred before the key press. In contrast, participants who experienced an immediate effect adaptation phase, judged only tones up to 20 ms after the action as occurring before the action. Thus, the constant experience of a delayed effect influenced perceived time of effect stimuli that deviated from their usual time. Stetson et al. assumed a temporal recalibration process because different sensory pathways (of actions and their sensation) are confounded by different delays. If effects occur with a constant delay, a sensory recalibration process takes place so that action and effect are perceived as occurring simultaneously (or at least they are perceived closer in time as they actually occurred). As a consequence of this sensory recalibration process, events that occur within this delay are perceived earlier. And thus effects that occur earlier than usual might even be perceived as occurring before the action.

It has been suggested that the bias to perceive actions and effects temporally closer as they actually are fosters the impression of the actor to be in control over the effect (Cravo, Claessens, & Baldo, 2009; Eagleman & Holcombe, 2002; Humphreys & Buehner, 2009). So, perceived agency and perceived time of an effect seem to be interrelated. On the one hand, an event in temporal proximity to an action is more likely perceived as an effect caused by the action. On the other hand, effects caused by an action, which were repeatedly experienced to occur after a constant delay, are perceived to occur earlier after the action than they actually occurred. However, to our knowledge this link between perceived causality and perceived time of action effects has never been tested directly.

Experiment 1

Previous research indicates that time alters the sense of agency, but research investigating the impact of temporal proximity on perceived causality has mostly neglected that the perception of time is by no means a pure representation of physical time. Consequently, we assume that it is not (only) physical temporal proximity that influences the immediate sense of agency, but that perceived time and the sense of agency are interrelated. To test this assumption, we let participants experience a constant delay between their action and a contingently following effect in the majority of trials, but in some trials we violated the temporal expectation and presented effects earlier or later than usual. To study the relationship of perceived time and experienced agency we collected both measures in trials in which the effect occurred either at the usual time, or earlier or later than usual. If agency judgments and time judgments rely on the same processes, they should be affected similar by this manipulation and thus the measures should correlate with each other.

Further, we varied group-wise whether participants usually experienced the action effect immediately after the action or with a delay of 250 ms. If the experience of a constant delay between action and effect induces sensory recalibration as suggested by Stetson et al. (2006), agency and time judgments should be influenced similarly by temporal deviations from the usual action-effect delay, irrespective of whether participants are adapted to immediate or delayed effects. Please note that the assumption of complete sensory recalibration predicts that agency and time judgments merely depend on temporal deviations from the usual action effect delay. Thus, for example, judgments should be similarly affected for the immediate and the delayed effect group when the effect occurs 100 ms later than usual. Thus, the recalibration account predicts that judgments are not determined by actual delays, e.g. whether the effect occurs 100 ms or 350 ms after the action in the respective groups adapted to immediate or 250 ms delayed effects. In contrast, if sensory recalibration is not complete and physical delays determine agency judgments, the judgments should differ in both groups and sense of agency should be largest for effects occurring closest after the action in both groups.

In this regard, we were especially interested in whether agency judgments are similar for immediate and delayed effects when the effect occurred at its usual time (that is, depending on experimental group either immediately or with a delay of 250 ms after the action). Previous research demonstrated that participants learned that effects occurred after action-specific delays (Haering & Kiesel, 2012) and further that knowledge acquired by experience influenced agency judgments (Buehner & May, 2003). We, therefore, assume that participants' sense of agency is similar for effects occurring at the usual time, irrespective of whether the effect occurs immediately or delayed by 250 ms depending on the participant's group.

To explore the time perception and to specifically test for sensory recalibration as observed by Stetson et al. (2006), we analyzed time judgments in more detail and additionally estimated psychometric functions based on the time judgments. If participants completely recalibrate to injected delays before an effect, time judgments should be similar for the immediate and the delayed effect group. In contrast, no or partial recalibration would be indicated by different time judgments in both groups.

Participants' task in our study was to move the mouse and click on the nose of a moose on the screen. In adaptation blocks, each mouse click triggered a bellowing sound after at the group-specific delay of 0 ms (immediate effect group) or 250 ms (delayed effect group). In test blocks, the sound occurred earlier than usual, at the group-specific delay, or later than usual in one third of the trials respectively. We varied temporal deviations from the usual effect time rather fine grained such that effects were presented (approximately) 200 ms, 150 ms, 100 ms, or 50 ms earlier or later than usual. Actually the occurrence of the sound was always bound to the participants' actions without participants being informed about this. When the sound occurred before the mouse click, the sound presentation was not triggered by the click, but by the mouse movement before the click (see method section for a detailed description). In test blocks participants either judged the time of the sound with reference to its usual time or they judged the experienced agency over the moose's bellowing.

Method

Participants. 39 students of the University of Wuerzburg participated due to course requirements. Three participants were excluded from analysis. Two of them had never rated the effect stimulus to have appeared “later than usual”. The third participant was excluded, because the 50% value of the psychometric function fitted to ‘later’ judgments differed more than three SDs from the group mean. Of the remaining 36 participants, 18 participants (mean age 20.2 years, 14 females, 2 left-handed) were in the immediate effect group and 18 participants (mean age 20.9 years, 14 females, 3 left-handed) were in the delayed effect group.

Apparatus and stimuli. E-Prime software (Schneider, Eschman, & Zuccolotto, 2002) run on a standard PC with a 17’’ CRT-screen (resolution of 800*600 pixels, 100 Hz refresh rate) was used for stimulus presentation and data collection. Acoustic stimuli were presented via VicFirth SIH-1 isolation headphones. Responses were collected with an optical mouse.

A red disk, the nose of Edgar the moose (see Figure 1), with a diameter of 96 pixels presented at the center of the screen served as target area. Participants moved the mouse cursor into the target area and then clicked the left mouse button. Clicking on Edgar’s nose resulted in a 50 ms tone that sounded like a moose bellowing.

---insert Figure 1 about here---

Design and Procedure. Each participant completed adaptation blocks and two types of test blocks, time judgment blocks and agency judgment blocks.

In adaptation blocks the picture of the moose with the red target area (the nose) remained on the screen throughout the block. Each trial started with a fixation cross centrally presented within the target area for 500 ms. Then the mouse cursor appeared 9.2 cm left of the center of the screen. Participants were instructed to move the cursor into the target area and then to press the left mouse key as fast as possible. After the mouse click, the moose bellowed either with no delay (immediate effect group) or with a delay of 250 ms (delayed effect group). The next trial started after an inter-trial interval of 1000 ms. If a mouse click missed the target area, an error sound and a written error message („Daneben! Bitte klicke nur auf die Nase!“, German for “Missed! Please click on the nose!“) were presented. When no mouse click was recorded within 1000 ms, participants were asked to respond faster (“Bitte schneller!”, German for “Faster, please!”). In both cases, the trial was repeated and restarted with the presentation of the fixation cross.

In test blocks, trials differed in two respects from trials in the adaptation blocks. First, the effect sound was presented at variable delays. The moose bellowed in one third of the trials at the same time as in adaptation blocks, in one third of the trials it bellowed earlier (approximately 50 ms, 100 ms, 150 ms or 200 ms) and in one third of the trials later (50 ms, 100 ms, 150 ms or 200 ms) than during adaptation blocks. Thus, in the immediate effect group, the moose bellowed prior to the actual mouse click. To present the sound before the mouse click, we had to estimate when a participant would click the mouse button. We based these estimations on the previous mouse movements of each participant in trials with usual delay. We recorded the x-coordinate of the mouse cursor 50 ms, 100 ms, 150 ms, and 200 ms before the mouse click and averaged these x-coordinates. To deal with systematic changes in movement speed throughout the experiment, averaging of the x- coordinates started anew in each adaptation block. Early effect sounds were triggered when the mouse crossed the respective x-position. This procedure enabled us to present the sound approximately 200 ms to 50 ms before the mouse click for participants in the immediate effect group. Yet, the actual presentation times differed from the predicted times due to different movement speeds in each trial. To present the early effects at comparable deviations in both experimental groups, we yoked participants in both groups regarding delays and trial order. When, for example, a participant in the immediate effect group had actually heard the effect 137 ms before his/her mouse click (instead of the intended 150 ms), the corresponding yoke participant experienced the effect 137 ms before the standard delay of 250 ms, i.e. 113 ms after the mouse click. This yoke design was chosen to present early effects with the same variability in both groups.

The second difference of test blocks compared to adaptation blocks was that after each effect the moose disappeared and participants were asked to judge either the time of the effect or the experienced agency. Agency judgments were given on a continuous scale ranging from 0% to 100%. This format has proven useful to assess agency judgments in recent studies (e.g. Buehner & Humphreys, 2010); it enables a more fine grained assessment of the sense of agency than an all-or none decision ("I caused the effect" vs. "I did not cause the effect"). Time judgments were collected as a three-staged judgment ("earlier", "as usual", "later"). Here we decided against a more fine-grained scale, because we wanted to know if participants detected temporal deviations (for similar procedures in the tradition of temporal judgments, see for example Aschersleben & Müsseler, 1999). In time test blocks, participants clicked in a box labeled with the respective time judgment (see Figure 1). In agency test blocks, participants answered by clicking on a horizontally presented scale ranging between 0% and 100% (see Figure 1). In both cases the chosen option (check box or position on the scale) was marked with a red "X" for 500 ms. An error tone and a written error message appeared when participants clicked outside the boxes for time judgments or more than 50 pixels above or below the scale for agency judgments, and no judgment was recorded (2.4% of all test trials).

Each participant accomplished 20 practice trials, followed by two adaptation blocks (40 trials each) resulting in 100 adaptation trials before the first test block. The seven test blocks consisted of 60 trials each. Test blocks 1, 3, 5, 6 and 7 asked for time judgments, test blocks 2 and 4 asked for agency judgments. After each test block one additional adaptation block with 40 trials followed to refresh adaptation to the standard delay. We included more time judgment than agency judgment blocks because we aimed to fit cumulative Gauss function for the time judgment data to estimate which temporal deviation from the usual time is recognized as a deviation from the usual effect time.

Data Analysis. All temporal deviations leading to effects earlier than usual are henceforth described as negative temporal values, i.e. a temporal deviation of -100 ms means that the effect was presented 100 ms earlier than usual, meaning that the effect occurred 100 ms prior to the mouse click in the immediate effect group and 150 ms after the mouse click in the delayed effect group. To gain a sufficient number of time and agency judgments per temporal deviation we aggregated early temporal deviations with respect to the actually planned categories of early temporal deviations (i.e. -200 ms, -150 ms, -100 ms and -50 ms). In detail, the judgments of all actual deviations between -225 ms and -176 ms, -175 ms to -126 ms, -125 and -76 ms, -75 ms and -26 ms, -25 ms and +24 ms, and between 24 ms and 75 ms were averaged as judgments of deviations of -200ms, -150 ms, -100 ms, -50 ms, 0 ms, and 50 ms respectively for each participant. This resulted in an average of 4.5, 13.6, 19.3, 17.0, 108.8, and 42.3 time judgments trials and in an average of 2.4, 6.1, 9.4, 6.7, 43.6, and 15.9 agency judgments trials for the respective time intervals for each participant.[1] In addition there were 23.8, 24.4, and 24.1 valid time judgment trials with deviation of 100 ms, 150 ms and 200 ms each and 9.9 valid agency judgment trials for each deviation of 100 ms, 150 ms, and 200 ms. Data from trials with actual deviations larger than -225 ms (4.2% of all trials in test blocks) were skipped from the analyses because they dispersed across a large range of early deviations.

[1] We had not expected positive temporal deviations to occur when a negative deviation was planned. However, this happened and therefore increased the planned trial numbers for 0 ms and 50 ms deviations in the test blocks. Here we initially planned 100 time judgment and 40 agency judgment trials for 0 ms deviation and 25 time judgment and 10 agency judgment trials for 50 ms deviation.

To compare time and agency judgments we calculated the percentage (relative frequency) of “time as usual” judgments and the mean percentage of sense of agency (i.e. the percentage to which participants felt to have caused the effect) separately for each participant for each of the 9 temporal deviations.

Results

Analysis of judgments. To compare agency judgments and judgments of the time of the effect stimulus, we computed the mean agency judgments and the arcsine-transformed mean percentage of “time as usual” judgments across the temporal deviations (-200 ms, -150 ms, -100 ms, -50 ms, 0 ms, 50 ms, 100 ms, 150 ms, 200 ms) separately for each participant (see Figure 2). We then correlated both judgments separately for each participant. In both groups the two judgment types were highly correlated with a mean r = .84 in the immediate effect group and a mean r = .59 in the delayed effect group. In order to compare correlation coefficients we used the Fisher’s r to Z transformation. Separate t-test for each group with the Fisher-transformed correlation coefficients indicated that correlations differed significantly from zero in the immediate effect group, $t(17) = 11.83$, $p < .001$, and in the delayed effect group, $t(17) = 7.30$, $p < .001$. A t-test revealed that the correlation coefficients between both groups differed significantly, $t(34) = 3.80$, $p = .001$.

---insert Figure 2 about here---

Further, we analyzed whether both judgment types (mean agency judgments and the arcsine-transformed mean percentage of “time as usual” judgments) were differentially affected by the temporal deviations from the usual effect times in both experimental groups. We used a mixed factors analysis as suggest by Dixon (2008) for the analysis of proportion data. Mean averages of the two judgments across temporal deviations for each group are depicted in Figure 3.

The mixed factors analysis with the repeated within-subject factors judgment type (time, agency) and temporal deviation (-200 ms, -150 ms, -100 ms, -50 ms, 0 ms, 50 ms, 100 ms, 150 ms, 200 ms) and the between-subjects factor group (immediate effect, delayed effect) revealed that the judgments varied across temporal deviations, $F(8, 118.09) = 86.45$, $p < .001$. In general, judgments were numerically largest for effects at the usual time. Compared to judgments at the usual time, judgments 50 ms after the usual time did not differ, $p = .47$, but judgments at any other temporal deviation were lower (all *p*s <= .001).

Further, there was a main effect of judgment type, $F(1, 502.68) = 28.98$, $p < .001$, which was moderated by an interaction of judgment type and temporal deviation, $F(8, 118.09) = 7.04$, $p < .001$. For the temporal deviations 100 ms, 150 ms and 200 ms, agency judgments were higher than time judgments (all *p*s <= .001) and they were marginally higher than time judgments for temporal deviations -200 ms and -150 ms (.05 < *p*s <= .06). For all other temporal deviations judgment type did not differ (*p*s > .14).

In addition, there was a main effect of group, $F(1, 502.68) = 171.34$, $p < .001$, that was moderated by an interaction of group and temporal deviation, $F(8, 118.09) = 87.28$, $p < .001$. Univariate comparisons between the average judgments (thus irrespective of judgment types) showed that judgments were lower for all negative deviations in the immediate effects group than in the delayed effects group (all *p*s < .001). For all positive deviations judgments were higher in the immediate effects group (all *p*s <= .005). If effects occurred at the usual time mean judgments did not differ between groups, $F(1, 67.81) = 0.34$, $p = .56$.

Judgment type did not vary differently between groups, $F(1, 502.68) = 0.61$, $p = .43$, and the pattern of judgment types across temporal deviations did not differ between groups, $F(8, 118.09) = 0.63$, $p = .74$ for the interaction between judgment type, temporal deviation and group.

---insert Figure 3 about here---

Time perception. To further analyze the perceived time of the effect we used the “earlier” and “later” judgments [2] (see Figure 3) and fitted cumulative Gaussian functions for each participant using the psignifit toolbox for MATLAB (Wichmann & Hill, 2001). The 50%-values of these functions were used as estimates which temporal deviation from the usual time is recognized as a deviation from the usual effect time. So, for example, if the 50%-value of a participant is at -20 ms for the earlier function and at +120 ms for the later function this means that an effect must occur at least -20 ms before the usual effect time to be predominantly recognized as “earlier as usual” and an effect must occur at least 120 ms after the usual time to be recognized as “later as usual”. Due to the complementary nature of judgments, this can also be interpreted such that effects occurring between -20 ms and +120 ms around the usual effect time are predominantly judged as occurring “as usual”.

To gain a measure of how consistent participants detected early respectively late temporal deviations, the difference limen (DL) around both the ‘earlier’ and the ‘later’ 50% values were calculated for each participant. The DL was calculated as the absolute difference between the 75% value and the 25% value of the respective psychometric function divided by 2. It reflects the steepness of the fitted functions and with this the consistency of time judgments. If for

[2] Please note that the functions for “earlier” and “later” judgments are complementary to the function of “same time as usual”-judgments, because the 50% values of these functions as well as the slope reflect the same information. That is, participants judged great negative deviations predominantly as “earlier”, great positive deviations as “later” and those in between as “as usual”. Yet, fitting psychometric functions to “earlier” and “later” judgments required less arbitrary decisions (see Figure 3) because some participants did not produce a unique maximum for earlier or later judgments, but for example judged 100% of the effect stimuli at the deviations -150 ms and -50 ms as “earlier”, but judged only 95% of effects at -100 ms as “earlier”.

example a participant consistently judged all deviations of +50 ms as “as usual” and all deviations of 100 ms as “later than usual”, the function will be very steep and the resulting DL very small.

We computed separate ANOVAs for both the 50% values and the DL with the between-subjects factor group (immediate effect, delayed effect) and the within-subject factor temporal judgment boundary (earlier, later). The analysis revealed a main effect of judgment boundary indicating that effects occurring earlier than usual were judged as early when they occurred 109 ms earlier whereas late effects were judged as late when they occurred 169 ms later than usual, F (1,34) = 160.15, $p < .001$., $\eta^2 = .83$. Further, there was a main effect of group, $F(1,34) = 16.51$, $p < .001$, $\eta^2 = .33$, which was moderated by an interaction with temporal judgment boundary, $F(1,34) = 4.56$, $p = .044$, $\eta^2 = .11$. Subsequent *t* tests revealed that participants of the immediate effect group judged the effect stimulus as early when it occurred 37 ms before its usual time, whereas participants of the delayed group judged an effect as early when it occurred 187 ms before the usual time, $t(34) = 3.59$, $p = .001$. In contrast, late effect stimuli were judged as late when they occurred 196 ms later than usual in the immediate effect group whereas effects occurring 138 ms later were judged as late in the delayed effect group, $t(34) = 2.52$, $p = .017$. Thus, the range between the earlier- and later-boundary was smaller in the immediate effect group (223 ms) than in the delayed effect group (328 ms), $t(34) = -2.19$, $p = .04$.

The analysis on DLs revealed a main effect of boundary due to a smaller DL for ‘earlier’ judgments compared to ‘later’ judgments (42 ms vs. 67 ms), $F(1,34) = 5.21$, $p = .029$, $\eta^2 = .13$. Additionally a main effect of group revealed overall smaller DLs in the immediate effect group compared to the delayed effect group (40 ms vs. 69 ms), $F(1,34) = 5.90$, $p = .021$, $\eta^2 = .15$. No interaction was found between the two factors, $F(1.34) = 1.47$, $p = .234$, $\eta^2 = .04$.

Discussion

Experiment 1 aimed to assess whether time perception and sense of agency are related, and in line with this assumption the current results revealed a high concordance of time and agency judgments for different temporal deviations from usual effect times. However, a trivial explanation for the high correlation of time and agency judgments could be the experimental procedure. For the same type of trials, participants either judged whether an effect occurred at its usual time or they judged the degree of agency over the effect. Most effect sounds occurred after the action and even when effect sounds occurred before the click, no effect sound appeared before the mouse was moved towards the target. Therefore, one might suspect that participants might have felt the same sense of agency in each trial, but searched for hints helping them to discriminate between experimental conditions to solve the task as wished by the experimenter. Here, the instructions that the effect sound could occur "earlier or later than usual" in test blocks and the task to discriminate between 'early', 'usual' and 'late' effects could have been taken as a hint that we expected the perceived early and late occurrence to be related to a decreased sense of agency. To rule out this suspicion, we ran a second experiment in which we assessed agency judgments only.

Experiment 2

In Experiment 2 the setting was the same as in Experiment 1, except that we cancelled out any reference to time. Thus, we did not ask for time judgments and we did not mention effect times during any instruction. We expect the pattern of agency judgments across temporal deviations to be similar to Experiment 1.

Method

Participants. 26 students of the University of Wuerzburg took part for 5 Euros or course requirements. 13 participants (mean age 27.8 years, 11 females, 13 right-handed) were in the immediate effect group and 13 participants (mean age 26.1 years, 10 females, 2 left-handed) were in the delayed effect group.

Apparatus & Stimuli. Apparatus and stimuli were the same as in Experiment 1.

Procedure. The procedure was the same as in Experiment 1 with the following exceptions. Each participant accomplished 20 practice trials, followed by two adaptation blocks (40 trials each) resulting in 100 adaptation trials before the first test block. Five agency judgment test blocks were administered. After each test block, participants performed one additional adaptation to refresh adaptation to the standard delay. Additionally the wording of the instructions differed. In Experiment 1 test blocks were described as blocks in which the moose could sometimes bellow before or after the usual time. In Experiment 2 each reference to time was deleted. Instead we instructed participants that in some blocks (i.e. the adaptation blocks) the mouse click always caused the sound whereas in other blocks (i.e. the test blocks) the control of the mouse click on the sound varied between trials.

Results

For each participant we calculated the mean agency judgment per temporal deviation. We conducted an ANOVA with the repeated within-subject factor temporal deviation (-200 ms, -150 ms, -100 ms, -50 ms, 0 ms, 50 ms, 100 ms, 150 ms, 200 ms) and the between-subjects factor group (immediate effect, delayed effect). The analysis showed a significant main effect of group, $F(1, 24) = 17.58$, $p < .001$, $\eta^2 = .42$, and of deviation, $F(8, 192) = 26.15$, $p < .001$, $\eta^2 = .52$, as well as an interaction of group and deviation, $F(8, 192) = 28.46$, $p < .001$, $\eta^2 = .54$.

Pairwise comparisons showed that agency judgments were lower in the immediate effect group for all negative deviations (all *p*s < .001). For effects at the usual time and all positive deviations the level of agency judgments did not differ (all *p*s >= .41).

Figure 4 shows the mean agency judgments in the immediate effect group and delayed effect group in Experiment 1 and Experiment 2. To check whether the agency judgments in Experiment 2 and Experiment 1 were similar, we computed separate ANOVAs for the immediate effects group and the delayed effects groups with the within-subject factor temporal deviation (-200 ms, -150 ms, -100 ms, -50 ms, 0 ms, 50 ms, 100 ms, 150 ms, 200 ms) and the between-subjects factor Experiment. For the immediate effects group, the main effect of deviation was significant, $F(8, 208) = 127.23$, $p < .001$, $\eta^2 = .83$, while the main effect of Experiment was not significant, $F(1,26) < 1$, but the interaction of Experiment and deviation was significant, $F(8, 208) = 2.38$, $p = .018$, $\eta^2 = .084$. Post-hoc comparisons indicated that agency judgments were significantly lower in Experiment 1 compared to Experiment 2 for the deviation -100 ms, $t(29) = 2.47$, $p = .02$, while for all other deviations agency judgments did not differ in both Experiments, *ps* >= .13. For the delayed effects group, the main effect of deviation was significant, $F(8, 208) = 12.42$, $p < .001$, $\eta^2 = .32$, but neither the main effect Experiment, $F(8, 208) = 2{,}18$, $p = .15$, $\eta^2 = .077$, nor the interaction of Experiment and deviation was significant, $F(8, 208) < 1$.

---insert Figure 4 about here---

Discussion

The perceived agency varied across temporal deviations in a similar way as in Experiment 1 although no reference to time was given. Like in Experiment 1, the level of agency was lower for early effects in the immediate effect group than the delayed effect group and did not differ for effects at the usual time. In contrast to Experiment 1, judgments were only numerically, but not significantly higher in the immediate effect group compared to the delayed effect group for all positive deviations of effect time.

The agency judgments in Experiment 1 and Experiment 2 were rather similar; they differed only for one temporal deviation (-100 ms) for the immediate effects group that is for one of 18 comparisons. This demonstrates that judgments in Experiment 1 reflect the immediate sense of agency and that this judgment is not biased because of the time judgments or the mentioning of time in the instruction. Thus, Experiment 2 replicates that the time of an effect in relation to its usual time influences perceived agency.

General Discussion

According to our knowledge, this study is the first attempt to directly compare time perception and sense of agency. We presented effects of an action either at its usual time, earlier or later than usual and asked participants in the same type of trials whether the effect occurred at its usual time and whether they sensed to have caused the effect. Participants were either adapted to immediate effects or to effects occurring 250 ms after the action. In both groups, the time judgments and the agency judgment were closely related to each other demonstrating that perceiving an effect at its usual time and sensing to have caused the effect are closely related.

To rule out any response biases due to the experimental procedure, we ran a second experiment with agency judgments only[3]. By comparing the agency judgments of Experiment 1 and 2, we were able to rule out that the agency judgments in Experiment 1 were biased. Thus, we can now turn to a closer inspection of the data of Experiment 1.

[3] Please note that we did not include a second control experiment to assess whether time judgments in Experiment 1 were biased because participants judged agency in the same experiment. We assume that time perception is much more direct than sense of agency because time judgments refer to physically existing time intervals. Thus, we do not expect that time judgments might become biased by simultaneous requests to judge agency.

First, we aimed to study the relationship of perceived time and experienced agency. Results revealed that participant's judgment whether an effect occurred at its usual time and their agency judgment correlated significantly in both groups. This correlation is in line with the hypothesis that both judgments rely on the same processes or are influenced by similar processes. Further, inspection of Figure 4 shows that time and agency judgments were rather similarly affected by temporal deviations, again indicating that the two judgment types were closely related. Yet, the mixed factor analysis also revealed an interaction of judgment type and temporal deviation because for extreme temporal deviations agency judgments were higher than time judgments while judgments did not differ if effects occurred at their usual time or with moderate temporal deviations. Currently, we can only speculate on the nature of this effect. Probably it emerged because of the different answer formats as the continuous agency judgments might show a trend towards the mean resulting in less reduced agency judgments for extreme temporal deviations. Alternatively, our procedure to assess time and agency judgments in separate blocks might lead to more pronounced differences than the alternative procedure to assess time and agency judgments in each single trial. We had refrained from such a procedure because we aimed to rule out that simultaneous assessments of time and agency judgments might overestimate the relation between both measures. Yet, future research might address this topic by comparing simultaneous judgments in the same trials with judgments assessed in separate blocks.

Interestingly, agency and time judgments differed more for effects occurring later than usual. We assume that this might reflect our experience with computers (or other technical equipment). Effects rarely appear earlier than usual because the delay occurs due to some necessary computing or loading time like an internet page that needs some time to load.

However, if effects appear later than usual, we can assume that this is because of a non-observable technical fault as for example a bad internet connection. This reasoning might explain why agency judgments were less affected by unusually late effects than time judgments. Please note, however, that negative and positive deviations differed regarding variability. Due to our experimental procedure to present effects prior to the action in the immediate effect group, we were not able to present the effect exactly 200, 150, 100, or 50 ms before the action. To equate conditions in delayed effect group, we decided to present early effects in the delayed effect group with the same variability. However, due to this procedure variability differed for early and late effects. It is therefore possible that temporal judgments were blurred for early effects especially in the delayed effect group in which the action did not serve as an anchor that the effect occurred before or after the action.

Second, we assessed time and agency judgments in two groups. One group usually experienced the effect immediately while in the other group the effect usually occurred with a delay of 250 ms. Interestingly, agency judgments for effects occurring at their usual effect time were similar in both groups. Thus, participants adapted to usually delayed effects (c.f. Haering & Kiesel, 2012) and sense of agency did not depend on physical time delays for effects occurring at the usual effect times. Further, agency judgments in both groups decreased for larger temporal deviation from the usual effect times. In the group with delayed effects, this means that agency judgments were larger when the effect occurred 150 ms to 250 ms after the action than when it occurred 50 ms or 100 ms after the action. So experience of a constant delay between action and effect in the past impacts on sense of agency because effects were less perceived to be caused by the action when they occurred after the action, but earlier than usual (for similar results see Haering & Kiesel, 2015). Consequently, prior experience of a delayed mechanism leads to knowledge which can be applied to deduce that an effect occurring earlier than possible due to the nature of the mechanism was not caused by the mechanism (Buehner & May, 2002; Buehner & McGregor, 2006). In this regard, our results are interesting with respect to the underlying mechanism of agency judgments. For example, sense of agency has been proposed to be related to the forward model (i.e. Haggard, 2005, Linser & Goschke, 2007). When an action is executed, the expected effect is anticipated. When the effect emerges, agency over its occurrence is sensed when the effect matches the expectation. Our results demonstrate that it is not only the effect that is anticipated, but also the time of its usual occurrence impacts on sense of agency. Our results are therefore in line with the assumption of Buehner & Humphreys (2009, 2010) that sense of agency depends on the belief in a causal action-effect relationship.

Nevertheless, physical proximity of action and effect had some impact on agency and time judgments. If effects occurred earlier or later than usual, time and agency judgments between both groups differed. First, in the immediate effect group early effects were reliably detected and did rarely induce any sense of agency. Thus, temporal proximity between action and effect does not induce any sense of agency if the order of both events is reversed. An action has to occur prior to the effect so that sense of agency of the effect evolves (e.g., Hume, 1739; Wegner & Wheatley, 1999) and the mere intention to cause an effect prior to its occurrence is not sufficient to induce sense of agency.

Second, participants in the immediate effects group were less sensitive to detect that effects occurred later as usual than participants in the delayed effects group. They more often judged late effects as occurring at the usual time and they experienced more sense of agency for late effects. In addition the correlation between time judgments and sense of agency was larger in the group with immediate effects than in the group with delayed effects. Thus, despite that participants adapted to usually delayed effects, this adaptation did not eliminate all group differences. Instead the current data are in line with the assumption of a partial sensory recalibration process as suggested by Stetson et al. (2006). The constant experience of a delayed effect influenced the perceived time of the effect, however, not to such a degree that the time judgments were influenced similarly by temporal deviations from the usual action-effect delay.

Closer inspection of the time judgment data support this assumption because analyses of the psychometric functions of 'earlier' and 'later' judgments revealed that the estimated values of early- and late-judgment boundaries in the two groups differed. Participants in the immediate effect group detected early effects at smaller absolute deviations than participants in the delayed effect group. In contrast, participants in the delayed effect group detected late effects at smaller absolute deviations than participants in the immediate effect group. When considering the overall range of temporal deviations that are still judged 'as usual' in both groups, this range is larger in the delayed effect group suggesting that participants with usually delayed effects are less sensitive to detect temporal deviations.

Less sensitivity for temporal deviations is also reflected in the DLs that are characterized by shallower slopes for participants in the delayed effect group. We assume that this occurs to due to task difficulty. Participants in the delayed effect group had to base their time judgments on the memorized effect time while all effect stimuli actually occurred after the action. In the immediate effect group, however, the action itself was available as temporal reference in all trials.

To conclude, we demonstrated that agency and time judgments vary similarly across temporal deviations of effects. In addition, the high correlation of judgment types indicates that judgments of both types highly coincide in both groups. Thus, perceiving an effect at its usual time and sensing to have caused the effect are closely related. In contrast, physical temporal proximity of actions and effects has only a minor impact on experienced agency.

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Figure 1. Schematic layout of the experimental design. In adaptation blocks, Edgar, the moose bellowed with a group-specific delay of either 0 ms or 250 ms after participants clicked on his nose. In adaptation blocks, this action effect either occurred earlier than usual, at the group-specific delay or later than usual. Participants either judged the time of the action effect or their sense of agency over the action effect.

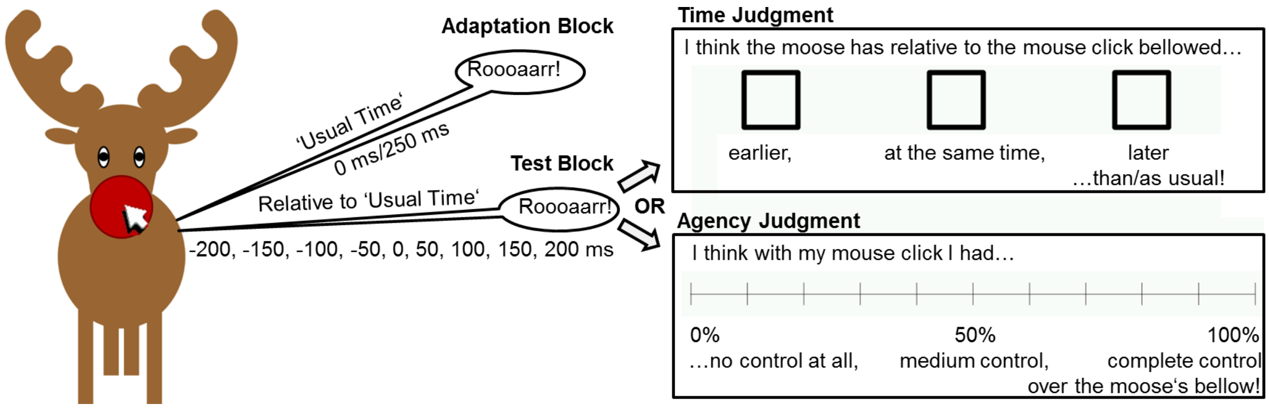


Figure 2. Correlation between the two judgment types depending on whether the effect usually occurred immediately or delayed.

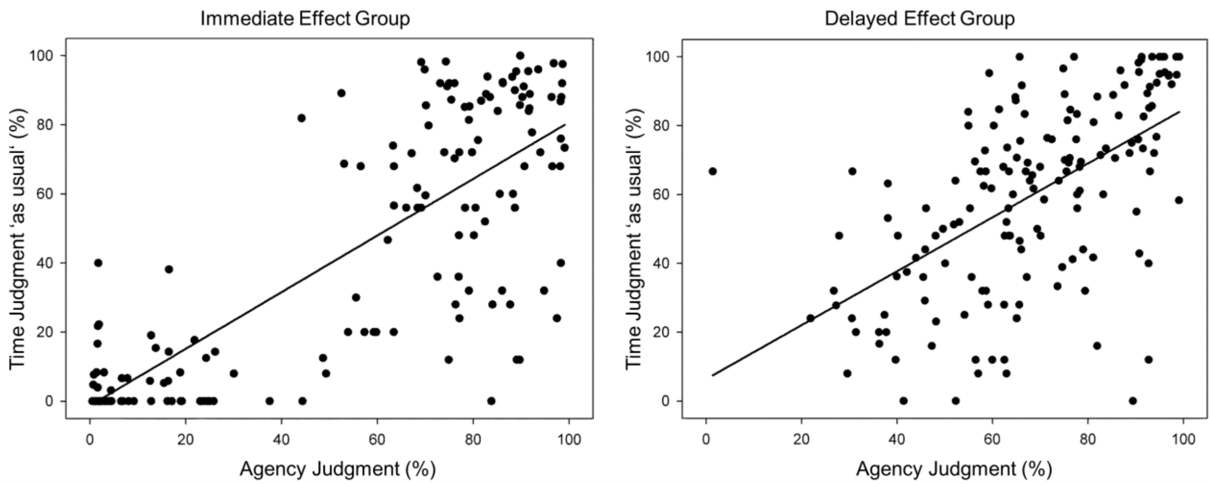


Figure 3. Mean proportion of time judgments (as usual, earlier than usual, later than usual) and average agency judgments across temporal deviations from the usual effect time for the immediate effect group and the delayed effect group respectively.

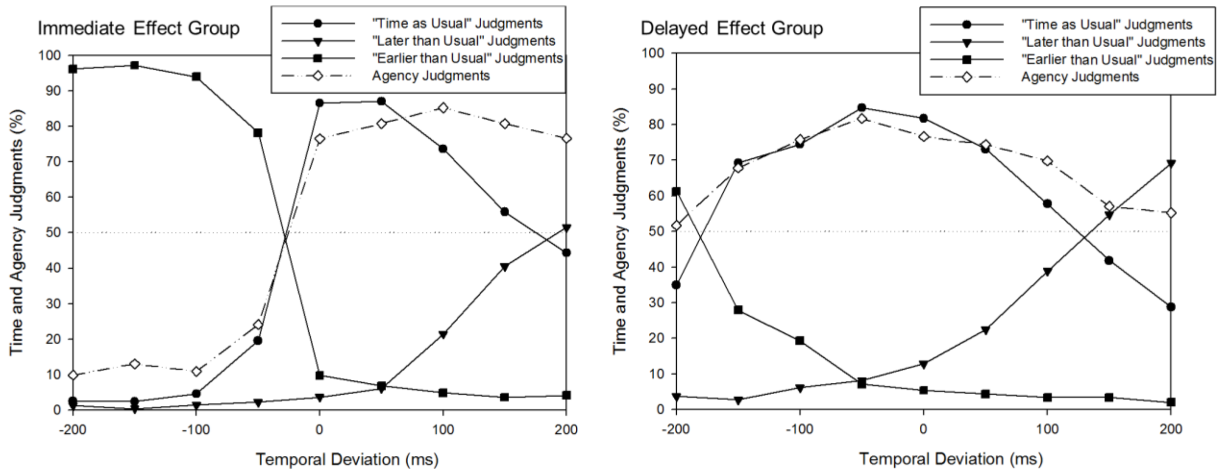
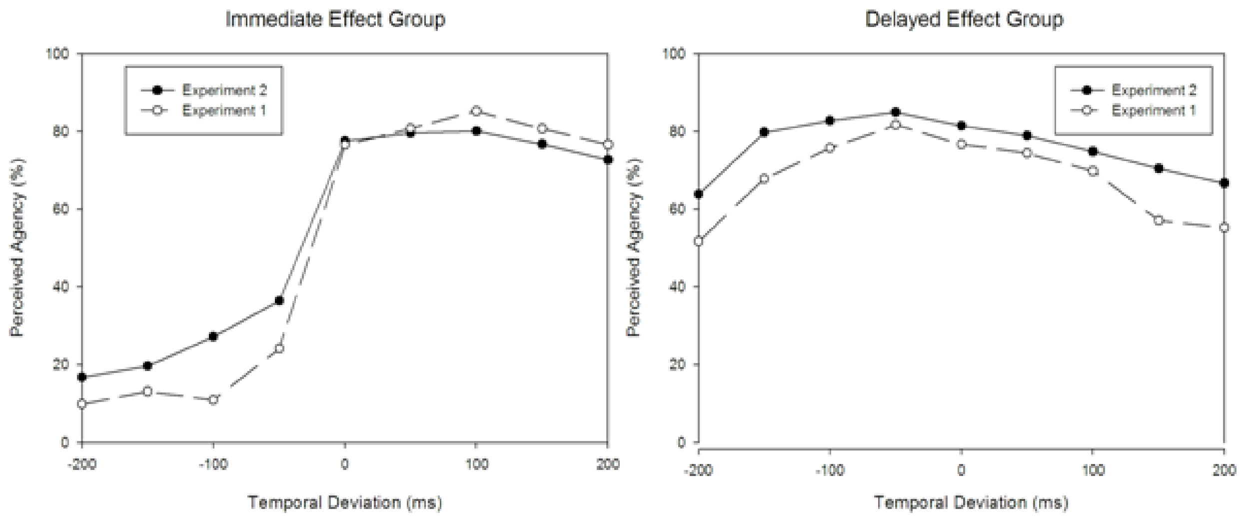


Figure 4. Mean agency judgments in the immediate effect group (left) and delayed effect group (right) in Experiment 1 and Experiment 2



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