Title: The Effect of Feedback and Reinforcement Learning on Time Perception
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Abstract:

Behavioral and electrophysiology studies have shown that humans possess a certain self-awareness of their individual timing ability. However, conflicting reports raise concerns about whether humans can discern the direction of their timing error, calling into question the extent of this temporal metacognition. To understand the depth of this ability, the impact of non-directional feedback and reinforcement learning on time perception were examined in a unique temporal reproduction paradigm that involved a mixed set of interval durations the opportunity to repeat every trial immediately after receiving feedback, essentially allowing a “re-do.” Within this task, we tested two groups of participants on versions where non-directional feedback was provided after every response, or not provided at all. Participants in both groups demonstrated reduced central tendency and exhibited significantly greater accuracy in the re-do trial temporal estimates, showcasing metacognitive ability and an inherent capacity to adjust temporal responses despite the lack of directional information or any feedback at all. Additionally, the feedback group also exhibited an increase in the precision of responses on the re-do trials, an effect not observed in the no-feedback group, suggesting that feedback may specifically reduce noise when making a temporal estimate. These findings enhance our understanding of timing self-awareness, and can provide insight into what may transpire when temporal metacognition or error monitoring is disrupted.

Introduction:

The tendency to reflect on one's mental state, or metacognition, is an essential human trait that is a central component of consciousness, memory processing, language, and decision-making, and, most importantly, time perception (Fleming and Dolan, 2012; Yeung & Summerfield, 2012). Accurate time perception is also a hallmark of consciousness and critical for everyday behaviors and cognitive functions ranging from speech, motor control, adaptive behavior, and survival (Grondin, 2010; Meck, 2005). Self-assessment of one's own timing ability without any external feedback is vital for reliably determining temporal accuracy and variance despite uncertainty (Balci et. al, 2011; Akdogan & Balci, 2017). Past research shows that humans and rodents can successfully incorporate the endogenous timing uncertainty and trial-by-trial variability associated with time perception tasks into their behavioral responses in a way that maximizes performance, updates temporal representations, and boosts reward (Balci et. al, 2011; Li & Dudman, 2013). Human performance is measured via interval timing tasks that instruct participants to estimate temporal intervals of several seconds (Buhisi & Meck, 2005). One particular task, temporal reproduction, involves exposure to a specific duration (encoding) and then an opportunity to re-create the interval duration via keypress (reproduction), with or without feedback. Previous research has shown that human subjects can accurately infer the distribution of intervals presented, and use this information to guide reproductions in the phase of measurement uncertainty (Jayzeri and Shalden, 2011; Acerbi, et al. 2012). While the evidence already points towards an intrinsic self-awareness of time, evaluating timing aptitude in context of feedback and learning may broaden our understanding of internal metacognitive process and its role in time perception.

Detecting and correcting errors is an important component for metacognition and self-awareness of one's cognitive state (Fleming and Dolan, 2012; Yeung & Summerfield, 2012). Error tracking mechanisms have been reported for temporal, numerosity, and spatial errors, implying that there may be a common metric error-monitoring system that underpins magnitude-based representations (Dunyan & Balci, 2019). In particular, temporal errors are a burgeoning area of research because the true extent of human cognizance related to time perception is not fully known, and related studies have produced conflicting results, particularly as it relates to the presence and type of feedback. Akdogan and Balci (2017) used a temporal reproduction task to assess how subjects reproduced a range supra-second intervals; their findings demonstrated that humans are aware of both the magnitude and direction (early/late) of their timing errors despite not receiving any external feedback. Another recent behavioral study used a temporal production task, in which subjects were asked to repeatedly produce a single duration (3s) and compared performance during a condition when only the magnitude of the error was given (absolute) against another condition in which both the magnitude and direction (signed) were given (Reimer, 2019). Signed feedback delivery yielded more behavioral adjustments in opposition to the direction of the error in subsequent trials, reduced bias in temporal estimates, and produced a more accurate and better calibrated performance when compared

to absolute feedback. This illustrated that directional information was not intrinsically accessible to the subject and that the participant's internal timing error representation failed to include that error direction. Furthermore, subjects assigned to the absolute feedback group also tended to report an over-reproduction of the interval duration when in reality, they were under-reproducing (Reimer, 2019). A key difference should be noted between these two studies, notably that feedback and retrospective self-judgments respectively were given following an entire block (Reimer, 2019) rather than trial-by-trial as in the Akdogan & Balci (2017) experiment. Task context also played a crucial role, as different tasks were used for the two studies; Akdogan & Balci (2017) employed a temporal reproduction with a mixed set of intervals while Reimer and colleagues (2019) used a temporal production task with a singly presented interval.

In addition to simply supplying knowledge and guidance about the response (Salmoni et. al, 1984), feedback has numerous other uses. It reduces response drifts over the experimental trajectory (Salmoni et. al, 1984, Reimer et.al, 2019) and may be erroneous or correct, but our study concentrates on correct feedback which tends to positively adjust behavioral responses (Salmoni et. al, 1984). Its delivery may be absolute – after every trial or on a percentage of trials (relative). Additionally, feedback can be a motivational factor and act as an implicit reward for behavioral learning (Tsukamoto et. al, 2006; Salmoni et. al, 1984). Post-error feedback can also facilitate the learning of time intervals (Ryan & Robey, 2002). Feedback may be processed differently depending on the quality of the learners, between low and high (Luft, 2013). Following feedback, high learners have greater theta connectivity from the left central cortices, which aligns with a well-functioning performance monitoring system (Luft, 2013).

Numerous studies demonstrate that there is an innate mindfulness of timing errors prior to and independent of the administration of feedback. In a recent M/EEG study utilizing a temporal production task with the objective of repeatedly producing the same single interval duration, Kononowicz and colleagues (2018) asked respondents to first judge their own performance. Afterwards, they were provided with 100% directional feedback in two blocks out of the six and 15% feedback on the remaining blocks. The initial self-assessment of their performance prior to feedback matched the true interval duration and beta power operated as an index of the actual duration and the self-evaluative ability to track timing errors (Kononowicz et. al, 2018). In yet another single duration temporal production study, Brocas and colleagues (2018) tasked participants to generate interval durations of 30+ seconds repeatedly for ten trials and introduced a reward scheme to incentivize making accurate temporal estimates. Similarly to Reimer's paradigm, participants accurately self-evaluated their performance after a block of trials and correctly identified what proportion of trials were above or below the target interval duration (Brocas et. al, 2018). Although accurate in their assessments of bias or tendency to over- or under-estimate, the participants were less successful in prediction beforehand or correction of their responses (Brocas et. al, 2018).

Evaluating the earliness or lateness in timing is dependent on a well-functioning neural performance monitoring system, a neural network devoted to adapting to changing behavioral conditions (Ullsperger et al, 2014). This system is also responsible for assessing and subsequently minimizing errors for seamless task execution and selection of appropriate motor programs (Ullsperger et al., 2014). Monitoring and updating temporal errors is further reflected in specific cortical oscillations traditionally associated with general error coding: frontal theta oscillations are modulated by error magnitude and possibly surprise and the delta phase at stimulus onset was correlated with future behavioral adjustments (Barne et. al, 2017).

Self-knowledge about your internal timing behavior also incorporates reinforcement learning, another adaptive behavioral operation that integrates previous experiences and applies them to future scenarios to improve outcomes and maximize future rewards (Lee et.al, 2012). Predicting the value of a set action along with its outcome and determining whether it will be awarded involves precise timing mechanisms (Petter et. al, 2018; Mikhael & Gershmann, 2019). Errors are prone to occur in this process, particularly when there is a mismatch between the expected and actual outcomes, manifesting itself in the form of a reward prediction error (RPE) (Hollerman & Schultz, 1998).

Notwithstanding errors, the process of learning interval durations transpires fairly quickly and is achieved with only one trial (Simen et. al, 2011). To measure the speed of temporal learning, Simen and colleagues (2011) devised the “beat-the-clock task”, a paradigm where a green square is displayed on a computer screen for an unknown amount of time. It remains onscreen until the appearance of a red square outline signals that the interval is ending. Participants must respond with a keypress before the stimulus terminates and are rewarded for on-time responses that are closer to the end time (Simen et. al, 2011). Although the task comprises of mixed interval durations that transition rapidly, early responding is minimized and on-time responding becomes the norm as participants learn the structure of the task.

Using an appropriate feedback technique is pivotal to understanding temporal metacognition. The traditional feedback structure in psychophysics studies is best suited for single interval reproductions because the same interval is successively reproduced; therefore, the majority of the studies described above are single interval experiments. Challenges arise when reproducing a random set of a mixed range of intervals because corrective guidance is given on one interval duration, yet the next interval may be of a different duration (Ryan, 2016). This is problematic since there is no opportunity to utilize the feedback from the previous trial to the new trial, so the feedback is frequently misapplied to an entirely different duration (Ryan, 2016). To rectify this issue, we introduced a “re-do” trial, which allows the subject to utilize the original feedback from the first trial in a second trial of the same duration. We hypothesized that the re-do trials will be beneficial to subjects for improving performance and in minimizing the Vierordt effect (underestimation of long intervals and overestimation of short intervals) (Ryan, 2016). It is for this reason our study also incorporated absolute (non-directional) feedback, to assess if subjects possess

awareness of the direction of the timing errors. If there is a substantial directional awareness of timing error, then the central tendency would be reduced.

Materials and Methods:

Subjects:

George Mason University undergraduates were recruited via flyers and through a posting in the George Mason research studies database. Eligible participants who completed the research study received undergraduate psychology course credit for their participation. Researchers gave each subject a questionnaire to determine eligibility prior to beginning the experiment. Participants with any neurological and psychological disorders, hospitalization for a psychological disorder, or diagnosis or treatment for substance abuse were excluded.

Twenty subjects each were originally recruited for Experiment I, which provided on- and off-target feedback. For the final analysis, data from only 17 right-handed neurologically healthy subjects (average age 20.8 years, 5 males, 3.84=SD) in Experiment I were analyzed. Two subjects did not fully understand the task parameters and one recruited subject later informed us that she had a concussion so these three were excluded.

Twenty right-handed subjects were also recruited for experiment II (no feedback); however, for the final data analysis, 19 right-handed subjects (average age 19.6 years, 6 males, 1.53 SD) were analyzed because one subject had outlier responses that varied three standard deviations from the average mean responses.

The difference in ages between Experiments I and II was also not significant $t(34) = 1.196$, $p = 0.245$. Additionally, a Pearson chi-square revealed that the gender ratio was not significantly different between the on/off and no feedback groups $\chi(1) = 0.020$, $p = .888$.

Task Paradigm:

Figure 1. Visual Temporal Reproduction Task.

Task schematic for the stages of the task (encoding, reproduction, feedback). A blue square is displayed for a randomized duration from 1-6 seconds and disappears on its own. A second blue square then appears and the

participant must press a number key to make it disappear once the on-screen duration time matches. Feedback indicating whether the participant was on- or off-target is then delivered. The participant then has a second opportunity to re-do the trial in its entirety.

The temporal reproduction task was delivered via Psychopy2 on a 27" Mac desktop while subjects sat ~60 cm from the computer screen (Dell S2716DGR, 120Hz refresh rate). The task structure comprised of three phases: estimation, reproduction, and feedback. These three phases were performed twice for each duration. Each trial initiated with a centrally presented fixation cross for a randomly presented duration of 2-6 seconds. In the estimation phase, a blue square was visually shown to the participant for one of five linearly-spaced, randomly presented intervals (1.5 – 6s). Until the square was on-screen, the participant was instructed to encode the duration in memory and to not use counting as a method to do so, which has been demonstrated as an effective means of eliminating counting strategies (Rattat-Voilet, 2011). Following the estimation phase, there was a 4-8 second gap prior to the reproduction phase. Then, the blue square reappeared on-screen in the reproduction phase and the participant was asked to press any number key when the blue square has remained on-screen for the same time duration as the time elapsed in the estimation phase. This keypress caused the square to disappear, signaling interval termination.

After every trial, adaptive feedback (duration=1s) was delivered 2-4 seconds after the disappearance of the square and informed the participant if the response was on-target or off-target; notably, this feedback provided no index of direction. Adaptive on- or off-target feedback started with an initial window of 30%. With subsequent trials, there is a 1% increase in the window with on-target responses and a 1% decrease with off-target responses. Critically, after each trial, participants had a second opportunity (essentially a re-do trial) to perform the entire sequence of phases (estimation, reproduction, and feedback) again, ensuring feedback will be applied to the appropriate duration.

In total, there are 120 trials (10 durations/block x 6 blocks x 2 trials). Participants were given a break after each block. We performed two versions of this task with one experimental condition with on/off feedback delivery and another experimental condition with no feedback at all. A different set of participants were used for each condition. In the first experiment, on and off-feedback was provided for both trials while the second experiment had two trials per duration but lacked any feedback.

Statistical Analysis:

SPSS 19.0 (IBM, SPSS) with alpha set to 0.05 was used to analyze the behavioral data from the temporal reproduction task in the two experimental groups independently and together. For both experiments I & II, the majority of the durations were normally distributed and passed the Shapiro-Wilks test of normality for both accuracy and precision (as measured by the coefficient of variation). The individual slopes and intercepts at each duration were also normally distributed for both experiments I and II. Repeated measures ANOVAs were performed for accuracy and precision and paired t-tests for comparisons within the first and

second trials. Separate analysis were conducted for each experiment. Then, comparisons between Experiments I and II were performed and repeated-measures ANOVA was conducted again and the independent t-test was used for the change (delta) in slopes and precision values between the first and second trials.

Results:

Experiment I:

Subjects administered the feedback version of the temporal reproduction task exhibited central tendency with over-estimation of short durations and under-estimations of long durations. The accuracy of the reproduced times for the first and second trials was compared and a significant main effect of duration ($F(2,12)=291.655$, $p<0.001$, $\eta=0.948$), of the trial ($F(1)=12.134$, $p=0.03$, $\eta=0.431$) and a trial x duration interaction ($F(2,297)=3.527$, $p=0.034$, $\eta=0.181$) were observed. Second trial estimates were more accurate and closer to the target durations, and there was less uncertainty in time estimation, as revealed by nearer estimations to the reference line or identity line. [Figure 2a].

Figure 2

a. Reproduction Accuracy for On/Off Feedback Condition: Participants exhibited significantly more accurate reproductions in the second trial compared to the first trial. Trial 1 is represented by the blue lines while Trial 2 is represented by the dotted red lines. The solid black reference line represents a perfect reproduction. Data are expressed in reproduced time $\pm$ SEM. **b. Temporal Precision for On/Off Feedback Condition** Participants were significantly more precise (lower coefficient of variations) in the second trial compared to the first trial. Trial 1 is represented by the blue lines while Trial 2 is represented by the dotted red lines. Data are expressed in the coefficient of variation $\pm$ SEM. **c. Temporal Certainty for On/Off Feedback Condition.** The slope of the second trial was significantly higher than the first trial and above the identity line. Data expressed in scatter plot with x and y coordinates corresponding to the first and second trial slopes, respectively of each individual participant.

The second trial time estimates were also more precise ($F(1)=9.398$, $p=0.007$, $\eta=0.370$), as measured by the lower coefficient of variation in the second trial estimates [Figure 2b]. Similar to accuracy, precision also exhibited a main effect of duration ($F(1,553)=8.862$, $p=0.002$, $\eta=0.356$) [Figure 2b]. Individual slope changes by trial type were compared and shown to be significantly higher $t(16)=-2.692$,

p=0.016 in the second trial and above the identity line, demonstrating more certainty in the estimates and less bias [Figure 2c].

Further dissection of the second trial reproduction estimates based on first trial feedback (on/off) was performed by separating the second trial reproduction time estimates based on whether the first trial was an off-target or on-target estimate. The redo trial estimates following positive feedback (on-target) time estimates trended closer to the target durations and identity line than negative (off-target feedback) but were not significantly more accurate ($F(1)=1.369$, $p=0.259$, $\eta=0.079$) unlike duration ($F(2.623)=163.236$, $p<0.001$, $\eta=0.91$) and trial x duration ($F(2.833)=5.434$, $p=0.003$, $\eta=0.254$) for the second trial which did significantly differ between feedback types [Figure 3a].

Figure 3

a. Second Trial Accuracy based on First Trial Performance for On/Off Feedback Condition Positive feedback (on-target) trended towards the target durations but was not significantly different from the negative (off-target) feedback. Positive feedback is represented by the solid purple and the negative feedback by the dotted green lines. Data are expressed in reproduced time $\pm$ SEM. **b. Second Trial Precision Depends on First Trial Performance for On/Off Feedback Condition** Positive (on-target) feedback in the first trial led to significantly higher precision (lower CVs) in the second trial. Positive feedback is represented by the solid purple and the negative feedback by the dotted green lines. Data are expressed in CV $\pm$ SEM. **c. Second Trial Slopes Depend on First Trial Performance for On/Off Feedback Condition** Slopes associated with positive feedback (on-target) in the first trial were significantly different from negative feedback (off-target). Data expressed in scatter plot with x and y coordinates corresponding to on-target and off-target slopes, respectively of each individual. The reference line represents a slope=1.

Positive feedback in the first trial resulted in significantly more precise estimates (lower CVs) in the second trial ($F(1)=8.106$, $p=0.012$, $\eta=0.336$) performance than negative feedback [Figure 3b]. The individual slopes of the redo trials $t(16)=4.699$, $p<0.001$ between the first trial positive (on) and negative feedback (off) also varied significantly, demonstrating more certainty in temporal estimation following positive feedback [Figure 3c].

Experiment II:

Similar to Experiment I, Experiment II subjects exhibited central tendency with subjects over-estimating short time intervals and under-estimating long time intervals. More accurate reproduced temporal estimates in the second trial for the no-feedback group signaled that they were reproducing the

time closer to the target duration with significant differences between the original and re-do trials ($F(1)=6.2$, $p=0.023$, $\eta=0.256$) [Figure 4a].

Figure 4

a. Reproduction Accuracy for No Feedback Condition Second trial duration reproductions were significantly more accurate than the first trial reproductions. Trial 1 is represented by the blue lines while Trial 2 is represented by the dotted red lines. The solid black reference line represents a perfect reproduction with each reproduced duration matching the target durations. Data are expressed in reproduced time $\pm$ SEM

b. Temporal Precision for No Feedback Condition Participants were not significantly more precise in the second trial compared to the first trial. Trial 1 is represented by the blue lines while Trial 2 is represented by the dotted red lines. Data are expressed in the coefficient of variation $\pm$ SEM

c. Slopes by Trial for No Feedback Condition The second trial slopes were significantly different higher from the first trial slopes with more participants above the identity line. Data expressed in a scatter plot with x and y coordinates corresponding to the first and second trial slopes, respectively of each individual. The reference line represents a slope=1.

Duration ($F(4)=123.03$, $p<0.01$, $\eta=0.872$) and the duration x time interaction ($F(18)=2.786$, $p=0.043$, $\eta=0.134$) also varied significantly between the trials despite the lack of feedback [Figure 4a]. Although more temporally accurate, subjects failed to show greater temporal precision, as evidenced by CVs in the re-do trials of the no-feedback version of the task ($F(1)=1.672$, $p=0.212$, $\eta=0.085$ [Figure 4b]. No significant differences in precision were observed in the duration ($F(4)=1.921$, $p=0.125$, $\eta=0.096$) or duration x trial ($F(4)=2.583$, $\eta=0.064$) [Figure 4b].

The individual slopes of the re-do trials displayed significantly greater certainty in the second trial temporal reproductions ($t(18)=2.33$, $p=0.021$ despite the lack of feedback [Figure 4c].

Experiment I & II Comparisons

For each subject participating in the on/off feedback and the no-feedback experiments, individual slope values for the second trial reproduced times were subtracted from the first trial reproduced interval estimates to compute delta slope values ($\text{slope}_{\text{trial2}} - \text{slope}_{\text{trial1}}$). The delta precision was also calculated for each subject ($\text{CV}_{\text{trial2}} - \text{CV}_{\text{trial1}}$) in the two experimental conditions. Notably, the on/off feedback group was significantly more precise (lower CV) than the no-feedback condition ($t(34)=3.234$, $p=0.003$ (CI:0.0223-0.09784) [Figure 5a].

Figure 5

a. Delta Precision between On/Off and No Feedback Conditions. Participants in the on/off feedback condition exhibited significantly reduced CVs (higher precision) when compared to the no-feedback condition. The solid black horizontal lines represent the averages of the delta precision values, 95% confidence intervals are represented by the outer boxes, and $\pm$ one standard deviation are represented by the inner boxes. Individual dots represent both sets of participants from the two conditions. The asterisk indicates a significant difference at $p < 0.05$. **b. Delta Slopes between On/Off and No Feedback Conditions.** The differences in slopes between the second and first trials (delta slope) were not significantly different when the on/off and no feedback conditions were compared. The solid black horizontal lines represent the averages of the delta slopes, 95% confidence intervals are represented by the outer boxes, and $\pm$ one standard deviation are represented by the inner boxes. Individual dots represent both sets of participants from the two conditions.

Due to the presence of outliers in the CVs, a Mann-Whitney U was performed ($U=62$, $z=-3.15$, $p=0.002$), further confirming the previous independent t-test results of significantly greater precision in the on/off feedback group.

An independent sample t-test also revealed no significant differences in the delta slope values between experiments, $t(34)=0.021$, $p=0.983$ (CI: -0.085-0.866) [Figure 5b].

Discussion:

Our study demonstrated the beneficial impacts of feedback when generating temporal estimates of short visual durations in the temporal reproduction task. Estimates tended to be more accurate and precise and reflected greater certainty when post-trial feedback indicated whether the response was on- or off-target. Furthermore, initial on-target feedback improved the precision and certainty of the second trial time estimation, as reflected by a reduced central tendency effect. Crucially, these benefits persisted despite the

fact that the feedback lacked informational content on direction indicating whether it was an under- or over reproduction of the interval duration.

Even without feedback, participants improved in the second re-do trials and demonstrated a smaller central tendency effect, suggesting that subjects are indeed metacognitively aware of the direction of their errors. However, precision did not improve when subjects did not receive feedback, signaling a more noisy estimate in the absence of feedback. Further comparison between the two groups (experiment I & II) revealed that only precision differed significantly between the two conditions of feedback and no feedback, highlighting that feedback is integral for making us more precise by potentially reducing measurement noise.

Notably, other studies confirm the role of feedback in enhancing the precision of temporal estimates. A recent study examined bias and variance changes for three time estimation tasks with a single interval design: motor reproduction, auditory comparison (duration discrimination) and auditory reproduction and found that in all three tasks, participants overestimated time durations (Shi et. al, 2013). Auditory feedback, included as a component of the auditory reproduction task, produced a lower overestimation bias and variance than the motor reproduction task, although the bias still surpassed the auditory comparison task. In this same study, the signal-to-noise (SNR) ratios were later manipulated to yield low and high SNR conditions and the variances on the reproduced interval, measured by standard deviations, were reduced in the high SNR condition compared to the low SNR in the same auditory reproduction task (Shi et. al, 2013). Similar benefits of auditory feedback have also been observed in Mitani and Kashino's (2018) experiment which required participants to reproduce the duration of a single tone after hearing it twice successively. Feedback was then delivered and participants indicated whether they were early or late in responding. Bias and variability improved, self-judgement of timing error matched the actual temporal reproductions, and serial dependency was dampened but only for subs-second rather than supra-second intervals (Mitani and Kashino, 2018). Our study extends the findings of these two studies to the visual modality and demonstrates a benefit in reducing timing variability in the longer supra-second range.

The type of feedback that is delivered plays a pivotal role in outcome. From our experiment I, the presence of positive on-target feedback specifically led to more precise temporal reproductions. A paradigm that can explain this behavior is the explore and exploit trade-off, an algorithm used in foraging related decision-making, which calculates the trade-off between selecting a choice with a known reward value rather than an alternative uncertain reward option with unknown value (Addicott et. al, 2017). Applied to our study, with positive feedback, participants exploited the known reward and temporal structure of the task to improve their temporal precision in their second redo trials (Navarro et. al, 2016). Conversely, when given negative feedback, subjects elected to "explore" other options and thus produced temporally variable reproductions when allowed to redo (Navarro et. al, 2016). Dopamine has been linked to both choices in the explore/exploit paradigm; at the subcortical level, genes controlling striatal DA function have been connected to the "exploit" selection and prefrontal DA function in catechol-O-methyltransferase

(COMT) has been associated with the “explore” selection (Frank et. al, 2009). Dopaminergic transmission has also been linked to timing and reinforcement learning due to sharing of striatal circuitry and association with reward (Coull & Nobre, 2008;. Jahanshahi, 2006). Prediction errors rely on the same dopaminergic circuitry; therefore, an increase or decrease in DA activation is reflective of positive and negative predictive errors, respectively (Schultz et. al, 1997, d’Ardenne et. al, 2008) and can influence perceived duration (Soares et. al, 2016). Related to this connection, Toren, Alberg and Paz (2020) recently performed a fMRI study with the time discrimination paradigm to explore how dopamine-mediated prediction error distorts time, revealing that negative prediction errors compress perceived duration while positive prediction errors dilate the perceived duration. This discovery was linked to activity in the putamen (Toren, Alberg & Paz, 2020).

The findings of our study have implications for a more extensive understanding of clinical conditions where temporal error monitoring is disrupted. Doeniyas and colleagues (2019) reported on autistic spectrum disorder (ASD) children who performed a no-feedback version of the auditory temporal reproduction task which also utilized confidence ratings and self-assessment of under- or over-reproductions. Performance-wise, ASD children achieved the task objectives and the mean reproduction accuracy and coefficient of variation demonstrated similarity to neurotypical children (Doeniyas et.al, 2019). However, there was a minimal match between the level of subjective self-confidence and actual objective performance in ASD children, suggesting that ASD children were unaware of temporal errors (Doeniyas et. al, 2019).

A few limitations of our study should be noted. There is need for more experimental groups and this expansion may include an additional feedback condition with directional (signed) feedback that informs the participant if it is an under- or over-reproduction. This is useful because it address the question of whether the internal representation of error includes directional information. Assessing participants’ self-confidence in their responses is also a critical item to examine in order to fully evaluate the degree of metacognition. Previous temporal metacognition studies have commonly included a post-trial self-assessment of participant performance prior to the provision of external feedback, the purpose of which is to correlate the level of confidence to the magnitude and the direction of the error in timing (eg, low confidence, huge error). The next iteration of our study could integrate an assessment of confidence to reinforce our claim of self-awareness of timing errors. Allowing subjects to use a sliding scale to mark how close they are to the target duration has been successfully used in prior studies, such as the M/EEG study of self-awareness during temporal production (Kononowicz et. al, 2018) or a more recent experiment investigating the influence of social modulation of being observed while performing the timing reproduction task (Oztel et.al, 2020). Finally, as the auditory modality has greater temporal resolution than the visual domain (Kanabus et. al, 2002) and is the privileged, dominant sensory domain in the area of time perception (Kanai et. al, 2011; Burr et. al, 2009; Guttman et.al, 2005), future studies may entail an auditory version of the temporal reproduction task.

Overall, our study deepens our understanding of temporal metacognition and shows that if corrective non-directional feedback is delivered on and tested on the same duration, it can be used to improve time perception and reduce the central tendency in mixed interval duration sets. Timing performance, excluding timing variability, remains uncompromised even in the absence of any feedback. This is aligned with human studies that have confirmed the ability to ascertain timing errors with confidence (Akdogan & Balci, 2017) and animal studies that reveal an innate awareness of temporal accuracy and prediction of success or failure in a uncertain environments (Balci et. al, 2009). Studying the impact of feedback and reinforcement learning on time contributes to a more nuanced appreciation of temporal processing and error monitoring in neurotypical populations, which can then potentially inform us about what transpires when timing mechanisms are disrupted. Finally, the behavioral results may be extended in future studies by using neuroimaging or EEG to uncover how temporal error monitoring and temporal metacognition are regulated at the neural level.

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