The Perception of Temporal Order can be Influenced by Retrospective Stimulation

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Abstract

When judging the order of presentation of the two visual stimuli (targets), if a preceding cue was presented around one of the targets, the target on the cue side was judged to have been given first (the pre-cue effect). In Experiment 1, a cue was presented after the target. As a result, it was found that the target on the cue side was judged to be presented later (post-cue effect). Experiment 2 confirmed the replicability of the post-cue effect by manipulating target-target onset asynchrony. Experiment 3 showed a post-cue effect in simultaneity judgments, demonstrating the robustness of this effect. The post-cue effect demonstrates that the process of judging temporal order or simultaneity is sensitive to stimulation shortly after the task-relevant stimuli, and may suggest that this process relates to the detection of movement direction.

Keywords: temporal-order perception, pre-cue effect, post-cue effect, temporal-order judgment, simultaneity judgment

Introduction

Understanding the temporal order of external stimuli is essential for understanding cognitive processes and everyday tasks. How does the brain determine the temporal order of input signals? Many studies have examined the process of temporal order perception by presenting task-irrelevant stimuli in addition to target stimuli whose temporal order is to be judged. For example, Hikosaka et al. (1993) examined how cueing affects the perception of the temporal order of visual stimuli. In their experiment, two visual stimuli (targets) were presented at different intervals and in different orders, and participants were asked to judge which target was presented first. A small dot of light (cue) was presented around one of the targets, 150 ms before the presentation of the two targets. The participants judged that the target on the side on which the cue was presented preceded the target on the opposite side by 30-70 ms. These values were similar to those obtained in other studies using visual (Stelmach & Herdman, 1991), auditory and tactile stimuli (Sternberg et al., 1971). Hikosaka et al. (1993) proposed that the onset of a visual stimulus (cue) accelerates local visual information processing, resulting in the earlier perception of another visual stimulus subsequently presented at the cue location.

Previous studies on temporal order perception have focused on factors before the presentation of targets. Do the factors after stimulus presentation affect the perception of temporal order? Several perceptual phenomena indicate that later stimuli affect earlier perceived stimuli (e.g., Shimojo, 2014). Backward masking is a typical retroactive phenomenon in which a visual stimulus is presented immediately after another at the exact location, making the previous stimulus invisible (Breitmeyer & Öğmen, 2006). Other examples of such retrospective phenomena include the color-phi phenomenon (Kolers & von Grünau, 1975, 1976), the flash-lag effect (Eagleman & Sejnowski, 2000), the chronostasis effect (Yarrow et al., 2001), the causal capture effect (Choi & Scholl, 2006), the attentional attraction effect (Ono & Watanabe, 2011), and backward illusory line motion (Ono et al., 2023). Based on an analogy with previous phenomena, we considered the possibility that factors after stimulus presentation may also influence the perception of temporal order.

The present study aimed to examine whether cues presented later influenced the perception of the temporal order of previously presented targets. In the present study, we extend the experiment of Hikosaka et al. (1993), who investigated the influence of a preceding cue by presenting it after the presentation of the targets. In Experiment 1, differences in cue-target onset asynchrony (CTOA) were used to examine how the effect of the cue on temporal-order judgments varied over time and the CTOA at which the effect of the later-presented cue was largest. In Experiment 2, using the CTOA that showed the most significant effect in Experiment

1, the left and right targets were presented at various onset asynchronies (target-target onset asynchrony, TTOA) to re-examine the effect of the later-presented cue. In Experiment 3, the effect of the later-presented cue was re-examined using simultaneity judgments.

In the present study, two accounts proposed by Ono (2024) concerning the perceptual processing of time duration were examined regarding the perception of temporal order. According to the *segmented time processing* account, the input of temporal information is terminated when the event for which the time to be judged has ended, and time judgments are made based on the information input up to that point. In other words, signals after the target presentation were not considered for time judgments. The segmented time processing account predicts that presenting a cue after the target does not affect temporal-order judgments because the input of temporal information has already been terminated. However, according to the *parallel time processing* account, there is a slight temporal delay between the end of the event for which the time should be judged and the final judgment, during which stimulus information is input and processed in parallel with time processing. In other words, the signal input during the processing of the event for which time is to be judged is considered for time judgments. The parallel time processing account predicts that presenting a cue after the target affects temporal-order judgments.

Experiment 1

In Experiment 1, the CTOA was set at a wide interval, including the time after the target presentation, to examine changes in temporal-order perception due to differences in CTOA. Hikosaka et al. (1993) showed that the CTOA changed temporal-order perception.

Method

Participants. A power analysis was performed to determine the required sample size. Because the effect size and other statistical values were not specifically reported by Hikosaka et al. (1993), an intermediate effect size (Cohen's $f = 0.25$) was used for the power analysis. An a priori power analysis was performed using G*Power 3.1 ($f = 0.25$, $\alpha = .05$, $1–\beta = .80$; Faul et al., 2007, 2009). The required sample size was 14. Thus, 14 participants (11 women and three men) aged 19–23 years were recruited (mean age 21.7 ± 1.3). All participants had normal or corrected vision and provided written informed consent before the experiment.

Apparatus and Stimuli. Figure 1a shows the trial timeline. Participants viewed the stimuli from approximately 60 cm on an LCD monitor (Dell AW2521HFL, refresh rate: 120 Hz) in a dimly lit quiet room. MATLAB 2021a and Psychophysics Toolbox Version 3 were used to program the experimental stimuli in this study (Brainard, 1997; Pelli, 1997). All the stimuli were presented against a black background on the screen. The initial display was a white fixation cross, 0.3° in diameter, located 1.1° below the center of the screen. The target consisted of two gray bars of 0.9° high and 0.2° wide. The bars were located 1.1° above the center of the screen and 1.1° to the left and right, respectively. The cue was a red or green circle, 0.8° in diameter, located 2.9° outward from the left and right targets. For half of the participants in all the experiments in this study, the cue was red, whereas for the other half, the cue was green, with red and green cues having the same luminance.

Procedure. The participants began each trial by tapping the spacebar. A fixation cross is then presented. One second after the appearance of the fixation cross, a cue or a target was presented. Following the experiment by Hikosaka et al. (1993), the left and right targets were presented asynchronously. The target-target onset asynchrony (TTOA) of the left and right targets were randomly chosen from four intervals (–33, –17, 17, and 33 ms). A negative TTOA indicated that the left target was presented before the right one, whereas a positive TTOA indicated that the right target was presented before the left one. The CTOA were randomly chosen from 12 intervals (–700, –400, –200, –100, –50, –17, 17, 50, 100, 200, 400, and 700 ms). A negative CTOA indicates that the cue was presented before the target (pre-cue), whereas a positive CTOA suggests that the cue was presented after the target (post-cue). CTOA was defined from the onset of the cue to the onset of the first appearing target when the CTOA was negative and from the onset of the second appearing target to the onset of the cue when the CTOA was positive. No cues were presented between the onsets of the first and second targets. Participants judged which of the two targets on the left or right was presented first (or second), and responded by pressing a key corresponding to their judgment (left or right). The cues and the targets were presented until the participant responded, after which all stimuli disappeared.

There were two cue location conditions (left or right), four TTOA conditions, 12 CTOA conditions, and four repetitions. Each participant completed 384 trials. The order of the trials was randomized across the participants. The experiment comprised two sessions (2 x 192 trials). Participants took a break after the first session. Half of the participants responded to the target that they thought was presented first in the first session, and to the target that they thought was presented second in the second session (the other half responded in reverse order). During the experiment, participants were allowed to take a short break whenever they wanted. Before the experiment, the participants were informed that the cue was not task-related and that they had completed 10 practice trials. Analyses were performed using R (version 4.2.1), R Studio (version 7.2.576), and HAD (Shimizu, 2016).

Results

Figure 1b shows the results of Experiment 1. Responses from the first and second sessions were combined. The outcome variable was the proportion of right targets to be judged first (left target judged to be second) under the left- and right-cue conditions. The average responses to the four TTOAs were calculated. Specifically, if there is no cue influence, the score is approximately 0.5.

A two-way analysis of variance (ANOVA) on the outcome variable with two within-subject variables (2 cue location conditions, 12 CTOA conditions) revealed no significant main effect of cue location ($F[1, 13] = 0.005$, $p = .943$, $\eta_p^2 < .001$). The main effect of CTOA and the interaction were significant ($F[11, 143] = 2.198$, $p = .019$, $\eta_p^2 = .145$; $F[11, 143] = 55.707$, $p < .001$, $\eta_p^2 = .811$). Huynh-Feldt correction was used for violations of the sphericity assumption (Huynh & Feldt, 1976). The multiple comparisons (Holm-Bonferroni method; Holm, 1979) revealed that the proportion of right target judged to be first (left target judged to be second) was significantly higher for the right cue than the left cue when the cue preceded the first stimulus onset by 100 ms ($t[13] = 4.406$, $p = .001$, Cohen's $d = 1.852$), 50 ms ($t[13] = 4.857$, $p < .001$, $d = 2.042$), and 17 ms ($t[13] = 3.405$, $p = .005$, $d = 1.431$) and that the proportion of right target judged to be first (left target judged to be second) was significantly lower for the right cue than the left cue when the cue was presented 17 ms ($t[13] = 5.608$, $p < .001$, $d = 2.358$), 50 ms ($t[13] = 5.808$, $p < .001$, $d = 2.442$), or 100 ms ($t[13] = 4.356$, $p = .001$, $d = 1.831$) after the second stimulus onset. The analyses showed that when the cue was presented before the target, the target on the cue side was judged to have been given earlier than opposite side. In comparing effect sizes, the pre-cue effect peaked at –50 ms CTOA. This result was nearly identical to that reported by Hikosaka et al. (1993). Surprisingly, when the cue was presented after the target, the target on the cue side was judged to have been presented later than on the opposite side. Compared to the effect sizes, the post-cue effect peaked at 50 ms for the CTOA. In the following experiments, we examine the replicability and robustness of the post-cue effect.

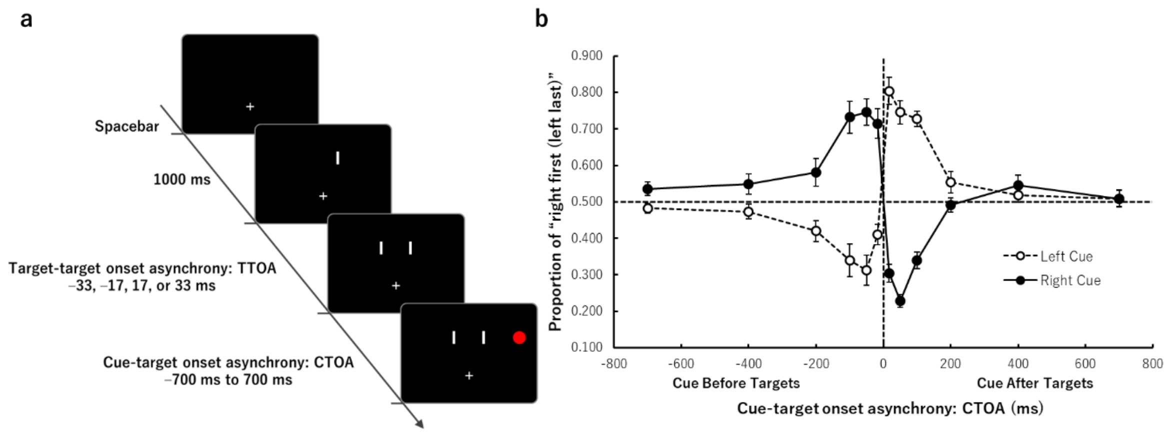

Figure 1. A sample trial and results of Experiment 1

(a) Timeline of a sample trial in Experiment 1. The cue and target were presented after the fixation cross (1 s). In some trials, the target appeared first (shown here); in other trials, the cue appeared first.

(b) Results of Experiment 1. The vertical axis represents the proportion of right targets judged to be first (left targets judged to be second). The horizontal axis represents the cue-target onset asynchrony (CTOA). Error bars indicate standard errors.

Experiment 2

In Experiment 2, the replicability of the post-cue effect was examined using CTOA, which yielded the most considerable post-cue effect in Experiment 1. The range of TTOA was expanded to explore the post-cue effect on peak CTOA more comprehensively.

Method

Participants. The results of Experiment 1 showed a significant effect size (Cohen's $d = 2.442$) when the CTOA was 50 ms. Because the analysis in Experiment 2 differed from that in Experiment 1 and an exact estimate of d was not valid, we used a large effect size ($d = 0.8$) for the power analysis. An a priori power analysis was performed using G*Power 3.1 ($d = 0.8$, α =.05, $1–\beta$ =.80). The required sample size was 15. The experiment consisted of two sessions, with half the participants responding to the target they thought was presented first in the first session and second in the second session (the other half responded in the reverse order). In counteracting this order effect, the total number of participants was set to 16, and 16 (12 women and four men) aged 18–24 years were recruited (mean age 21.9 ± 1.6).

Apparatus and Stimuli. The apparatus and stimuli were the same as those used in Experiment 1.

Procedure. The trial sequence was the same as in Experiment 1, except for the following points. First, the CTOA was fixed at 50 ms. The TTOA was randomly chosen from nine intervals (–67, –33, –17, –8, 0, 8, 17, 33, 67 ms). There were two cue location conditions (left or right), 9 TTOA conditions, and 16 repetitions. Each participant completed a total of 288 trials.

Results

Figure 2a shows the results of Experiment 2. Responses from the first and second sessions were combined. The outcome variable was the point of subjective simultaneity (PSS). The PSS was defined as the intersection of the sigmoid curve and the horizontal line, indicating $P = 0.5$. For model fitting, the probit-transformed value of the proportion of right targets judged to be first (left targets judged to be second) was regressed (probit regression analysis). The maximum likelihood method was used for the estimation. The mean PSS was 34.600 ms (SE = 3.399) for the right-cue condition and –39.566 ms (SE = 3.448) for the left-cue condition. For the analysis, a normal distribution was assumed. The results of the Kolmogorov-Smirnov test did not indicate that the data were not normally distributed. A *t*-test of the outcome variable revealed that the PSS of the right-cue condition was significantly larger than that of the left-cue condition [$t(15) = 13.415$, $p < .001$, $d = 5.452$]. The analysis showed that when the cue was presented immediately after the target, the target on the cue side was perceived as being presented later; thus, the post-cue effect could be replicated. In the next experiment, the robustness of the post-cue effect was examined using a simultaneity judgment task.

Experiment 3

In Experiments 1 and 2, the participants judged the order of presentation of the left and right targets (temporal-order judgments). In addition to temporal-order judgment, simultaneity judgment is another representative judgment method used in temporal-order perception studies. In simultaneity judgments, participants judge whether the timing of the presentation of the two targets is simultaneous.

Method

Participants. Following the same criteria as in Experiment 2, a large effect size ($d = 0.8$) was used for power analysis. An a priori power analysis was performed using G*Power 3.1 ($d = 0.8$, $\alpha = .05$, $1 - \beta = .80$). The required sample size was 15, and 15 participants (13 women and two men) aged 20–23 years were recruited (mean age 21.6 ± 1.2).

Apparatus and Stimuli. The apparatus and stimuli were the same as those used in Experiments 1 and 2.

Procedure. The trial sequence was the same as in Experiment 2, except the participants judged whether the left and right targets were presented simultaneously.

Results

Figure 2b shows the results of Experiment 3. The outcome variable was the PSS. To estimate PSS, each participant's data were fitted with the difference of two cumulative Gaussians. We used MATLAB 2021a and SimultaneityDiffCumGaussMultistart function (Yarrow et al., 2011; Yarrow et al., 2016) to fit the data. The model has three parameters (low boundary, high boundary, and standard deviation of the cumulative Gaussian distribution for both boundaries). This study defined the mean of the low and high boundary as PSS. The mean PSS was 2.600 ms (SE = 0.962) for the right-cue condition and –4.182 ms (SE = 1.477) for the left-cue condition. For the analysis, a normal distribution was assumed. The results of the Kolmogorov-Smirnov test did not indicate that the data were not normally distributed. A t-test of the outcome variable revealed that the PSS for the right-cue condition was significantly larger than that for the left-cue condition [$t(14) = 3.051$, $p = .009$, $d = 1.415$]. This analysis showed a post-cue effect in the simultaneity judgment task.

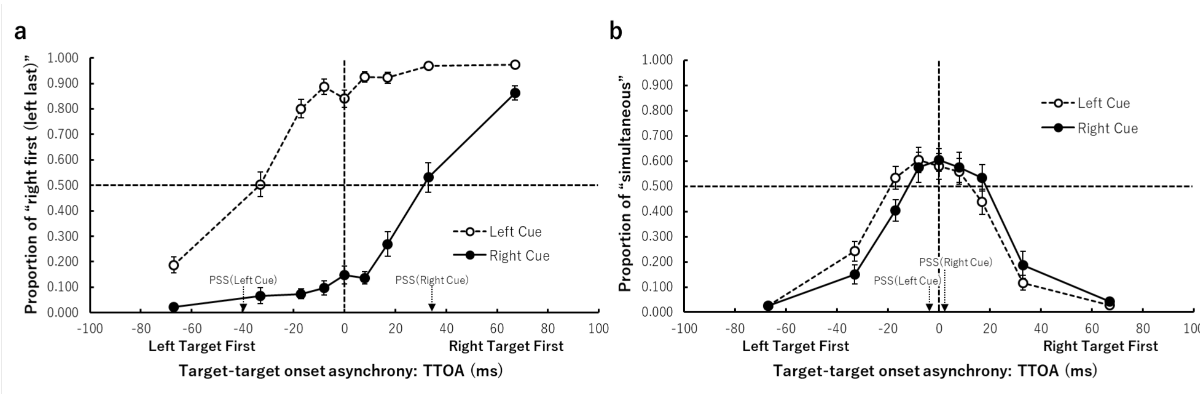

Figure 2. Results of Experiments 2 and 3

(a) Results of Experiment 2. The vertical axis represents the proportion of right targets judged to be first (left targets judged to be second). The horizontal axis represents the target-target onset asynchrony (TTOA). Error bars indicate standard errors.

(b) Results of Experiment 3. The vertical axis represents the proportion of simultaneous judgments of the left and right targets. The horizontal axis represents the TTOA. Error bars indicate standard errors.

Discussion

The results of these experiments showed that when the cue was presented after the target, the target on the cue side was judged to have been presented later. This observation is consistent with the *parallel time processing* account, in which time processing and information input occur parallel until a final decision is made. The findings of this study are significant in two respects. First, retrospective factors influence the perception of temporal order. Second, the influence was opposite to the cue before the target presentation. As a mechanism for the pre-cue effect, Hikosaka et al. (1993) proposed that the presentation of a cue accelerates local visual information processing, resulting in the earlier perception of another visual stimulus presented following the cue location. However, the post-cue effect indicates delayed processing of targets around the cue, which the faster visual processing of the cue cannot explain.

Yamamoto and Kitazawa (2001) showed that the tactile temporal-order judgments were reversed with a time difference of approximately 0.3 s when the hands were crossed. They proposed the hypothesis that the temporal order of two consecutive events is reconstructed in the brain by the cooperation of two different regions, one representing the motion between two consecutive signals and the other representing the two events themselves (motion projection hypothesis; see also Kitazawa et al., 2007; Takahashi et al., 2013). We propose that the modulation of temporal-order judgments by motion projection also occurs between visual cues and targets (Figure 3). Precisely, when the cue is presented first, the target on the cue side is perceived as if it was presented first (pre-cue effect) owing to the apparent motion from the peripheral cue to the center where the targets are located. Conversely, if the cue is presented later, the target on the cue side is perceived as if it was presented later (post-cue effect) owing to the apparent motion from the center where the targets are located to the surrounding cue. Additionally, the fact that the pre-cue and post-cue effects in Experiment 1 were significant only for short CTOAs up to ±100 ms supports this interpretation based on motion projection.

In Experiment 3, which examined the post-cueing effect using the simultaneity judgment task, the difference in PSS was approximately 5 ms. This value was smaller than the difference in PSS obtained using temporal-order judgments in Experiment 2 (approximately 74 ms). It is well-established that the results obtained from simultaneous and temporal-order judgments can differ. For example, the phenomenon of stimuli to which attention is directed appears earlier than stimuli to which attention is not directed (prior-entry effect) and tends to be smaller in magnitude when assessed by performance on simultaneity judgments than when assessed by performance on temporal-order judgments (Schneider & Bavelier, 2003; Van der

Burg et al., 2008; see Spence & Parise, 2010, for a review). Neurophysiological studies have shown that temporal-order judgments involve more processes than simultaneity judgments (e.g., Miyazaki et al., 2016). Thus, the large post-cue effect obtained with temporal-order judgments may be due to the involvement of more perceptual processes than with simultaneity judgments. In addition, decision or response bias is a possible cause of a large post-cue effect. It has been noted that the PSS derived from temporal-order judgments is influenced more by decision and response biases than is the PSS derived from simultaneity judgments (García-Pérez & Alcalá-Quintana, 2015; Vatakis et al., 2008). In temporal-order judgments, the participants were forced to indicate that one stimulus appeared first, even if they perceived them simultaneously. When simultaneity was perceived, the participants preferentially judged or responded that the cued stimulus appeared later, which may have led to the large post-cue effect observed in this study.

This study presented no cues between the first and second targets. Morein-Zamir, Soto-Faraco, and Kingstone (2003) have reported that sounds presented before and after two flashes improved temporal-order judgments in visual temporal-order judgments. In contrast, sounds presented between the two flashes hindered performance. In the experimental situation of this study, presenting the cue between the first and second targets would affect the apparent motion. It may produce different results than if the cue were presented before or after the target.

The results of this study suggest a new perspective for the study of temporal order: retrospective factors. However, it remains unclear which processes generate the post-cue effect. Further research is needed to clarify the mechanism underlying the post-cue effect, such as experiments that manipulate apparent motion by stimulation across multiple modalities or by presenting cues between targets.

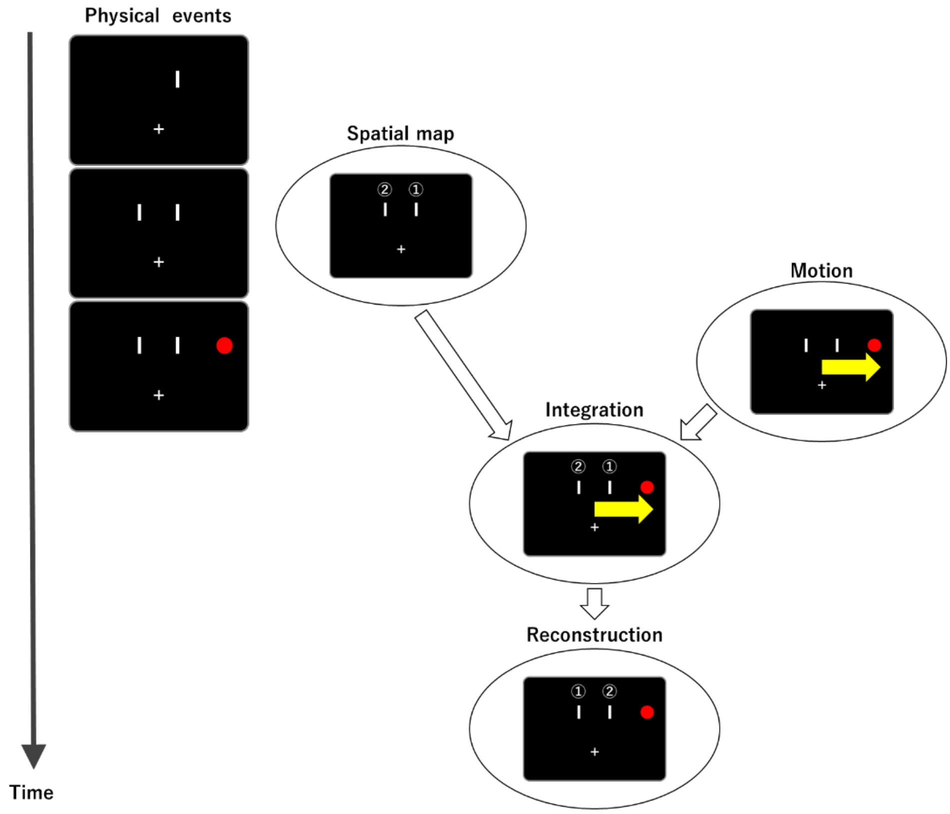

Figure 3. Modulation of temporal-order judgments by motion projection

Hypothetical process of the modulation of time-order judgments by post-cue. For example, when the right target is presented before the left, it is mapped in space as "one on the right and two on the left". However, when the cue was presented to the right immediately after that, motion occurred from the center where the targets were located to the right. It is then remapped as "two on the right and one on the left" when the spatial map and the motion information are integrated.

Declarations

Funding

This study was supported by the JSPS KAKENHI (grant number: 21K03132).

Conflicts of interest

The authors declare no potential conflicts of interest with respect to the research, authorship, or publication of this article.

Ethics approval

This study was approved by the Ethics Committee of Yamaguchi University (No.2018-001-02). The experiments were conducted in accordance with the Declaration of Helsinki guidelines.

Consent to participate

Written informed consent was obtained from all participants before the experiment.

Open Practices Statement

The experimental design and analysis plan for this study have been preregistered with the Open Science Framework (OSF) website at https://osf.io/r9spz/.

Author's contributions

F. Ono is the sole author involved in the conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing of the original draft, and review and editing of the manuscript.

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