

# Sounding and imagining sounds improve visual time perception: Application of the modality effect of time perception

*Perception*

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[journals.sagepub.com/home/pec](https://journals.sagepub.com/home/pec)**Shasha Wei, Yu Tian , and Jiajin Yuan**

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**Abstract**

This study examines whether the modality effect can be used to improve visual time perception. In Experiment 1, we used a time-reproduction task to explore the accuracy (i.e., deviation of reproduced time from veridical time) and precision (i.e., variability of reproduced time) of time perception under auditory, visual, or audiovisual conditions. Results confirmed the existence of a modality effect. Experiments 2a and 2b and Experiment 3 examined whether adding auditory stimuli improves visual time perception. In Experiments 2a and 2b, participants were required to sound when the visual stimuli appeared. Results showed that the addition of sound to visual stimuli perception is associated with higher time perception accuracy than viewing visual stimuli alone. Given that sounding is not always applicable, we conducted Experiment 3, with participants asked to imagine sounds instead of sounding. Results showed that imaginary sounds improved accuracy. However, in Experiments 2a, 2b, and 3, neither sounding nor imagining sounds changed the precision of time perception. The findings of this study indicate that adding auditory stimuli reliably improves the accuracy of visual-time perception, irrespective of whether the sound is real or imagined.

**Keywords**

sounding, imagining sounds, modality effect, time perception, application

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Time perception has a modality effect, suggesting that auditory stimuli are perceived more accurately and precisely than visual stimuli. The simultaneous presentation of auditory and visual stimuli may lead to a higher accuracy of time perception than the presentation of visual stimuli alone. Precise time perception is crucial for fundamental human actions, motor activities, and social interaction. However, where physical time flows evenly, time perception is subjective and can be distorted by the internal state of the perceiver and external features of the stimulus (Briker et al., 2021; Lake, 2016; Li & Tian, 2020; Martinelli & Droit-Volet, 2022; Ren et al., 2021; Zhou et al., 2021).

Over the decades, many studies have focused on the effect of the stimulation modality on time perception, especially visual and auditory stimuli. Empirical evidence suggests that auditory and visual presentation times are perceived differently. For example, based on participants reproducing the perceived time of a light or tone by pressing a button, Walker and Scott (1981) showed that auditory time perception was longer at 1,000 and 1,500 ms. Further analysis indicated that time perception was significantly more precise at 1,500 ms as it was closer to the objective presentation time. Meanwhile, in Wearden et al.'s (1998) study, participants were asked to verbally estimate the presentation time of stimuli (77–1183 ms) in either the auditory or visual modality. Results showed that auditory stimuli produced longer average verbal estimations than those of visual stimuli, and the coefficients of variation (standard deviation/mean) of the estimations were higher for visual stimuli than for auditory stimuli. Similarly, Droit-Volet et al. (2004) conducted a bisection task that required participants to judge whether the presented stimulus time (300–700 ms) was close to the short or long anchor (200 ms vs. 800 ms). In doing so, they found that participants tended to make more “long” evaluations for auditory stimuli than for visual stimuli. Furthermore, the curve fitted by the “long” evaluation indicated that auditory time perception was closer to the objective presentation time than visual time perception. This suggests that auditory stimuli are perceived as longer and more accurate than visual stimuli. Such empirical evidence indicates that auditory stimuli are generally perceived as longer and more accurate than visual stimuli with the same presentation time.

The effect of modality on time perception can be explained using the pacemaker-accumulator (PA) model (Church, 1984; Gibbon et al., 1984; Treisman, 1963). The PA model posits three main components for generating time perception: an arousal-related pacemaker, attention-controlled switch or gate, and accumulator. During timing, the pacemaker emits pulses that pass through the switch or gate and are collected by the accumulator. The number of accumulated pulses represents an individual's perception of time. In PA models, increasing arousal is conceptualized as an acceleration of the pacemaker rate, and higher arousal accelerates the emission of pulses (Lake et al., 2016; Mella et al., 2011; Piovesan et al., 2018; Vallet et al., 2019). Simultaneously, the switch or gate is conceptualized as a controller that allocates attention to timing; the more attention to timing, the more pulses through the switch or gate (Bar-Haim et al., 2010; Brown, 1997; Lejeune, 1998; Zakay & Block, 1996). Based on the PA model, Wearden et al. (1998, 2006) describe the modality effect on time perception as the “pacemaker speed,” in which auditory coding generates more “clock ticks” per unit of time than visual coding. Therefore, auditory stimuli generate more pulses for a given time, resulting in less loss per unit of time and thus more accurate time perception than visual stimuli. Alternatively, Meck (1984) and Penney et al. (2000, 2003) explain such a modality effect in terms of attention, as auditory stimuli are easier to capture and maintain attention to than visual stimuli. According to this explanation, auditory stimuli pass through switches or gates more efficiently than visual stimuli, resulting in more accurate time perception. Significantly, although these two explanations of the modality effect on time perception focus on pacemaker rate and attention, respectively, they both conclude that auditory stimuli lead to more accurate time perception than visual stimuli.

More importantly, according to the PA model, auditory and visual stimuli share a common psychological representation of time perception, inferring that the modality effect could improve visual

time perception as auditory time perception is more accurate. In this respect, Glenberg and Swanson (1986) proposed an account of modality effects based on time coding, with time information coding for auditory events considered superior to visual ones. Therefore, auditory information may represent an effective compensatory strategy to overcome visual sensory deficits. Several studies demonstrate that the simultaneous presentation of auditory and visual stimuli improves timing accuracy compared to presenting visual stimuli alone (Plummer & Humphrey, 2009; Walker & Scott, 1981). In addition to the PA model, recent studies have shown auditory dominance over vision, rather than their optimal integration in time perception (Burr et al., 2009; Gori et al., 2012; Ortega et al., 2014; Walker & Scott, 1981). For instance, Burr et al. (2009) quantitatively examined the relative contributions of visual and auditory stimuli to audiovisual stimuli, finding that sound tends to dominate the perceived timing of audiovisual stimuli. Consequently, the audiovisual modality increased in accuracy compared with the visual modality. These results indicate that the addition of auditory stimuli may improve the accuracy of visual time perception.

Humans can simultaneously sound while receiving visual information, such as when viewing a stimulus. It is reasonable to expect individuals to improve their visual time perception by sounding when they perceive visual stimuli. Moreover, some studies have found that imagining a sound produces auditory processing similar to that of sounding (Dharmapeera et al., 2020; Halpern & Zatorre, 1999; Herholz et al., 2008, 2009; Zatorre & Halpern, 2005). As such, if sounding improves visual time perception, it follows that imagining a sound may also improve visual time perception.

In view of the foregoing, this study tests whether the accuracy (i.e., deviation of reproduced time from veridical time) of visual time perception is improved by generating auditory information. This study also analyzes the variability of participants' evaluations and determines whether precision (i.e., less variability) is improved by adding auditory information. To achieve this, we designed four sequential experiments. Experiment 1 replicates the modality effect (i.e., visual, auditory, and audiovisual modalities). Based on previous findings, we hypothesize that both auditory and audiovisual time perception will be more accurate and precise than visual time perception (Hypothesis 1). Experiments 2a and 2b explore whether sounding when visual stimuli appear improves visual-time perception. In this regard, we hypothesize that sounding when visual stimuli appear results in a more accurate and precise time perception (Hypothesis 2). Experiment 3 compares the effects of imagining a sound on visual time perception. We hypothesize that imagining a sound when visual stimuli appear will improve the accuracy and precision of visual time perception (Hypothesis 3). This study uses a temporal reproduction task to measure time perception (1000–4000 ms), with “beep” used for both real and imagined sounds.

## Experiment 1

### Method

**Participants.** A total of 29 participants (22 women,  $M_{\text{age}} = 22.62$ ,  $SD = 2.24$ ) with normal or corrected-to-normal vision and no hearing problems were invited to participate in this study. Sample size was determined using an *a priori* power analysis. The power analysis indicated that a sample size of 28 participants would be appropriate to detect a medium modality effect with a power of 0.8 at an alpha of 0.05.

Previous studies indicate that participants' emotional states, such as anxiety and depression, may affect their time perception (Droit-Volet et al., 2020; Martinelli et al., 2021). Accordingly, we controlled for the effect of emotion and included data as covariates in statistical analyses when necessary. Prior to conducting the experiment, participants' emotional states were assessed using the following three questionnaires: the State-Trait Anxiety Scale (Spielberger et al., 1970), Beck Depression Inventory (Beck et al., 1961), and the Positive and Negative Affect Scale (Watson et al., 1988).

Results showed low state anxiety ( $M \pm SD = 33.03 \pm 5.29$ ), depression ( $M \pm SD = 3.83 \pm 3.84$ ), the PA score ( $M \pm SD = 31.24 \pm 7.57$ ), and the NA score ( $M \pm SD = 27.43 \pm 8.29$ ).

For all experiments reported in this paper, all participants provided informed consent for the experimental procedure per the ethical principles of the latest revision of the Declaration of Helsinki. Ethical approval for this study was provided by the ethics committee of the Institute of Brain and Psychological Sciences, Sichuan Normal University.

**Materials.** In this experiment, the auditory stimulus was a tone with a frequency of 800 Hz and loudness of approximately 60 dB produced by a computer speaker. The visual stimulus was a white square ( $135 \times 135$  pixels) presented at the center of a computer screen with a gray background. The tone was faded in and out for 4 ms to make the sound appear smooth. In the audiovisual condition, a visual stimulus was presented simultaneously with a sound stimulus. In this typical time-reproduction experiment, participants were presented with stimuli through different modalities (i.e., visual, auditory, and audiovisual) but were not told its length and had to replicate it as accurately as possible by pressing a key on a keyboard.

**Design.** Experiment 1 used a  $3 \times 4$  within-subjects design. The dependent variables were the standard deviation (*SD*) of the reproduction and accuracy index, as follows:

$$\left| 1 - \frac{\text{mean reproduction time}}{\text{actual presentation time}} \right|$$

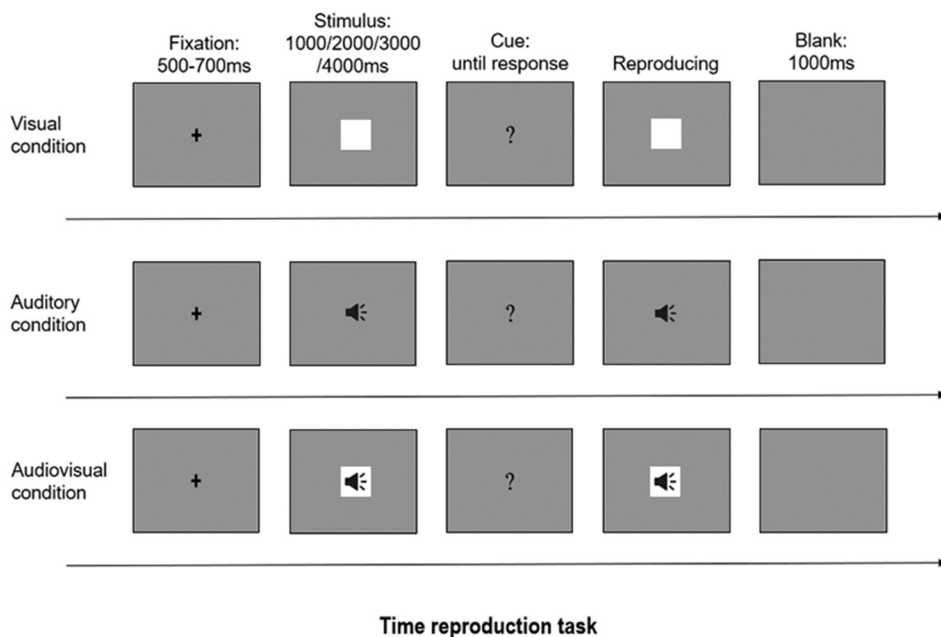
The foregoing equation represents the accuracy of reproduction, with a smaller score indicating higher accuracy in terms of time perception. *SD* refers to the variability and precision of the reproduction. Previous studies suggest that visual stimuli have a larger *SD* than auditory stimuli because visual stimuli have a slower pacemaker rate than auditory intervals (Bratzke & Ulrich, 2019; Wearden et al., 1998). The independent variables were: (a) stimulus modality—visual, auditory, or audiovisual; and (b) presentation time of stimulus—1,000, 2,000, 3,000, and 4,000 ms.

**Procedure.** Experiment 1 was conducted and recorded using E-Prime 2.0 (Psychological Software Tools, Pittsburgh, PA, United States) on a PC. Stimuli were presented on a monitor ( $1920 \times 1080$  pixels, 60 HZ) and the reaction equipment was a keyboard. Participants were comfortably seated in a quiet room, approximately 60 cm from the monitor.

For the visual condition, each trial started with a fixation cross for 500–700 ms, followed by a white square presented for 1,000, 2,000, 3,000, or 4,000 ms. Subsequently, a question mark appeared on the screen, cueing the participant to reproduce the time of the white square presentation. The question mark remained on the screen until the participant responded by pressing the spacebar, with the pressing time subjectively equivalent to the presentation time of the white square. An image of a white square with a gray background appeared at the beginning of the keypress and remained until the participants released the spacebar. Finally, a 1,000 ms blank was presented (Figure 1). For this process, participants were instructed avoid adopting any strategies for counting the presentation time of the stimuli.

The experimental procedure for the auditory condition was the same as that for the visual condition with two exceptions: a “beep” sound emitted by the computer speaker was used instead of a white square, and participants are required to reproduce the time of the sound they had just heard. At the time of reproduction, a “beep” sound appeared at the beginning of the keypress and remained until the participants released the spacebar.

The audiovisual condition was identical to the visual condition except that the visual stimulus was replaced by the simultaneous presentation of a sound and a white square. Participants were



**Figure 1.** The procedure of Experiment 1. Schematic illustration of the time reproduction task in visual, auditory, and audiovisual conditions.

required to reproduce the previous presentation time. Similarly, a sound and a white square simultaneously appeared in place of a white square during the reproduction.

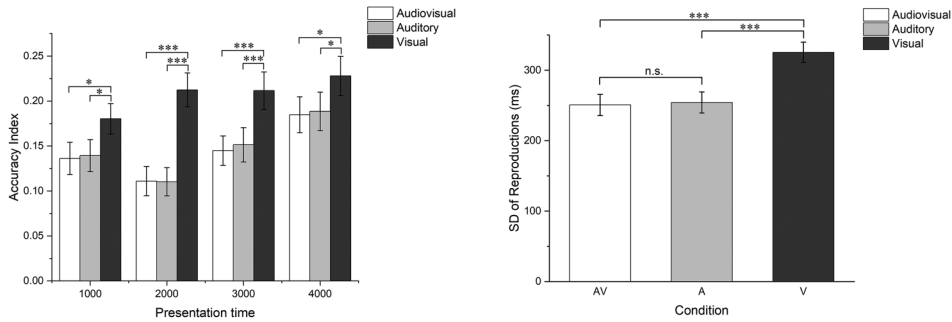
Participants completed all three conditions, totaling 180 trials. For each condition, 60 trials (15 for each presentation time) were presented randomly to minimize the order and fatigue effects. Furthermore, there was a 1-min rest between conditions. The order of the conditions was randomized across participants using the Latin square method. As there were no correct answers for this task, no feedback was provided. Before starting the experimental session, participants were allowed to practice preparatory exercises until they were familiar with the procedure.

## Results

This study conducted two-way repeated-measures analysis of variance (ANOVA) on the accuracy index and *SD* of reproduction, with stimulus modality (visual, auditory, and audiovisual) and presentation time (1,000, 2,000, 3,000, and 4,000 ms) serving as within-subject variables.

**Accuracy Index.** Results showed significant main effects of modality,  $F(2, 28) = 19.41, p < .001, \eta_p^2 = 0.41$ ; presentation time,  $F(3, 28) = 7.07, p < .01, \eta_p^2 = 0.20$ ; and an effective modality by stimulus presentation time interaction,  $F(6, 28) = 3.13, p < .05, \eta_p^2 = 0.10$ . As Figure 2 shows, simple effect analysis revealed that both auditory and audiovisual modalities were more accurate than visual modalities for all presentation times. Moreover, according to the paired comparison results, the difference between the audiovisual and visual conditions was most significant at 2,000 ms ( $p < .001$ ).

**Variability in Reproduction.** Regarding the *SD* of reproduction, results demonstrated significant main effects of modality,  $F(2, 28) = 16.76, p < .001, \eta_p^2 = 0.37$ ; and presentation time,  $F(3, 28) = 79.86,$



**Figure 2.** Accuracy (left panel) and precision (right panel) of reproduction across the four presentation time in audiovisual, auditory, and visual conditions.

Note: Error bars represent the standard error. ns = not significant. \* $p < .05$ , \*\*\* $p < .001$ .

$p < .001$ ,  $\eta_p^2 = 0.74$ . However, no interaction between modality and presentation time was observed,  $F(6, 28) = 0.87$ ,  $p = .52$ ,  $\eta_p^2 = 0.03$ . *Post-hoc* tests showed that both audiovisual and auditory modalities had smaller *SD* of reproduction than the visual modality. More specifically, although the variability increased with time duration, there was no difference between them (see Figure 2). This indicates that reproduction was more variable for visual than for auditory and audiovisual modalities. These findings replicate the modality effect based on the two aspects of performance mentioned above, indicating that auditory and audiovisual stimuli are perceived more accurately and precisely than visual stimuli.

## Discussion

Experiment 1 tested whether the modality effect of time perception exists. To confirm Hypothesis 1, we assessed the accuracy and precision of time perception in the visual, auditory, and audiovisual modalities. Results confirmed that auditory and audiovisual time perception were more accurate and precise than visual time perception. These results are consistent with those of previous studies (Burr et al., 2009; Droit-Volet et al., 2007; Goldstone & Goldfarb, 1964; Gori et al., 2012; Ortega et al., 2014; Plummer & Humphrey, 2009; Walker & Scott, 1981; Wearden et al., 1998) and support Hypothesis 1, namely, that auditory stimuli can be used to improve visual time perception.

## Experiment 2a

Experiment 1 found that the auditory and audiovisual modalities were more accurate and precise than the visual modality. More specifically, the modality effect indicated that the addition of auditory stimuli improved visual time perception. However, although auditory stimuli are superior in terms of time perception, they are not always presented in the auditory modality of our lives. That said, auditory stimuli can be added to time perception through sounds. Accordingly, Experiment 2a compared the visual condition to the “sounding + visual” condition in order to test whether sounding when visual stimuli appear improves visual time perception. Participants were asked to sound when visual stimuli appeared. If the accuracy or precision of time perception was higher in the “sounding + visual” condition than in the visual condition, it would suggest that adding auditory stimuli can improve visual time perception. As the difference between audiovisual and visual modalities was most significant at 2,000 ms, we tested the accuracy and precision of time perception at 2,000 ms in Experiments 2a, 2b, and 3.

## Method

**Participants.** A total of 30 participants (25 women,  $M_{\text{age}} = 21.43$ ,  $SD = 2.42$ ) with normal or corrected-to-normal vision and no hearing problems participated in this study. Participants were determined using the *a priori* power analysis used in Experiment 1, with results indicating that 28 participants were sufficient for Experiment 2a. The participants completed the same questionnaire as that used in Experiment 1. The results showed low state anxiety ( $M \pm SD = 37.67 \pm 8.83$ ), low depression ( $M \pm SD = 5.6 \pm 4.87$ ), the PA score ( $M \pm SD = 27.43 \pm 8.29$ ), and the NA score ( $M \pm SD = 14 \pm 5.39$ ).

**Materials.** The instruments and materials used in Experiment 2 were identical to those used in Experiment 1. Experiment 2 had three conditions: visual, auditory, and “sounding + visual.” The visual and auditory conditions were the same as those in Experiment 1. In the “sounding + visual” condition, only a visual stimulus was presented and participants had to produce a sound when they saw the visual stimulus. More specifically, participants were asked to make a “beep” sound at the beginning of the white square presentation until it disappeared, and then reproduce a subjectively equivalent presentation time by pressing the spacebar. Similar to the presentation phase, only a white square was presented during the reproduction phase. Therefore, participants were required to make a “beep” sound during the presentation of the white square.

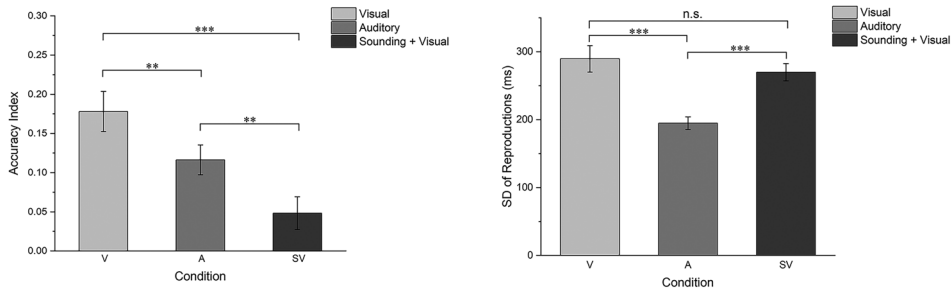
**Design and Procedure.** A one-factor (i.e., stimulus modality) within-subject design was adopted for Experiment 2, with the same dependent variables as those used in Experiment 1. The procedure was identical to that of Experiment 1, except that a new condition and different presentation times were used. In each condition, the presentation times were 80% of 2,000 ms and only 10% of 1,000 and 3,000 ms, totaling 40 trials. Participants completed three conditions, making for a total of 120 trials. For each condition, 40 trials (32 trials for 2,000 ms, 4 for 1,000 ms, and 4 for 3,000 ms) were presented randomly to minimize order and fatigue effects. The order of the conditions was randomized across participants using the Latin square method.

## Results

We analyzed the data of 2,000 ms in three conditions.

**Accuracy Index.** A repeated-measures ANOVA with stimuli modality (three levels: “visual,” “auditory,” “sounding + visual”) confirmed a significant difference in the accuracy index for the three conditions,  $F(2, 58) = 23.13$ ,  $p < .001$ ,  $\eta_p^2 = 0.44$ . *Post-hoc* analysis showed that the “sounding + visual” condition ( $M = 0.05$ ) was more accurate than the auditory condition ( $M = 0.12$ ),  $t(29) = 3.78$ ,  $p < .01$ , and visual condition ( $M = 0.18$ ),  $t(29) = 6.19$ ,  $p < .001$ . The auditory condition was also more accurate than the visual condition,  $t(29) = 3.44$ ,  $p < .01$  (Figure 3). These results indicate that auditory stimuli improve visual time perception through sounding.

**Variability in Reproduction.** Results also revealed the main effect of stimulus modality on the *SD* of reproduction,  $F(2, 58) = 19.23$ ,  $p < .001$ ,  $\eta_p^2 = 0.40$ . *Post-hoc* analysis showed that the auditory condition ( $M = 194.87$ ) was less variable than both the visual condition ( $M = 289.61$ ),  $t(29) = 5.30$ ,  $p < .001$ , and the “sounding + visual” condition ( $M = 269.77$ ),  $t(29) = 5.84$ ,  $p < .001$ . However, as Figure 3 shows, there was no significant difference between the “sounding + visual” and visual conditions ( $p = .77$ ). These results suggest that the auditory modality was more precise than the visual modality, but that the addition of auditory stimuli via sounding did not improve the precision of reproduction.



**Figure 3.** Accuracy (left panel) and precision (right panel) of reproduction across the auditory, visual, and sounding + visual conditions.

Note: Error bars represent the standard error. ns = not significant. \*\* $p < .01$ , \*\*\* $p < .001$ .

The results of Experiment 2a suggest that auditory stimuli can improve the accuracy of visual time perception through sounding. However, auditory stimuli had no effect on the precision of the visual time perception.

## Discussion

In Experiment 2a, we tested whether adding auditory stimuli to visual time perception improved the accuracy of visual modality. The results of the accuracy index showed that sounding when visual stimuli appeared improved visual time perception. Therefore, Experiment 2a replicated the modality effect in both Experiment 1 and previous studies (Droit-Volet et al., 2007; Goldstone & Goldfarb, 1964; Plummer & Humphrey, 2009; Walker & Scott, 1981; Wearden et al., 1998). It also confirmed our hypothesis that sounding can be used to improve visual-time perception.

However, in respect to the *SD* of reproduction, we did not observe a decrease in variability via sounding, suggesting that the effect of sounding on visual time perception may only reflect accuracy. Interestingly, the results of the accuracy index indicated that the “sounding + visual” condition had a more accurate performance than the auditory condition. If the “sounding + visual” condition were to only add auditory stimuli to the timing, then the accuracy index between the two should be similar. As such, other factors, such as vocalization-producing actions, may affect time perception. Certainly, there is increasing evidence that action and perception interact with timing processing (Anobile et al., 2020; Kroger-Costa et al., 2013; Petrizzo et al., 2022; Press et al., 2014; Sayalı et al., 2018; Yokosaka et al., 2015). For example, research indicates that finger movements or walking increases the perceived duration of concurrent stimuli (Kroger-Costa et al., 2013; Press et al., 2014; Sayalı et al., 2018). The phenomenon of movement extending perceived duration can be interpreted as an action that enhances internal clock speed (Petrizzo et al., 2022; Sayalı et al., 2018; Wearden et al., 1999).

## Experiment 2b

In Experiment 2a, we found that sounding improved visual time perception and the “sounding + visual” condition was more accurate than the auditory condition. Several studies have suggested that actions may be involved in the process of sounding (e.g., Petrizzo et al., 2022; Sayalı et al., 2018; Wearden et al., 1999). Accordingly, in Experiment 2b, we added a control group and asked participants to simulate the sounding condition in order to clarify which factor defined the accuracy improvement reported in the “sounding + visual” condition.

## Method

**Participants.** A total of 28 participants (21 women,  $M_{\text{age}}=24.29$ ,  $SD=0.71$ ) participated in Experiment 2b, per the same *a priori* power analysis used in Experiment 1. Participants had normal or corrected-to-normal vision and no hearing problems.

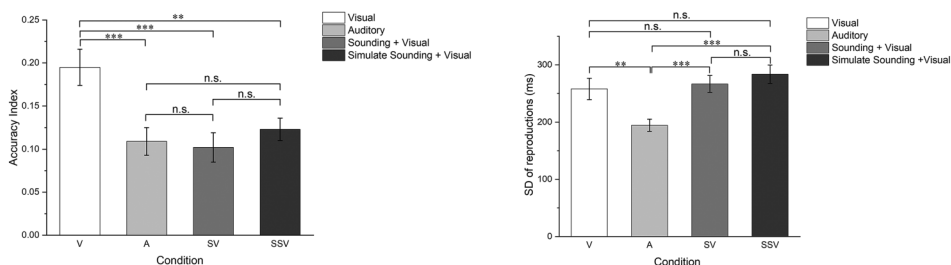
**Materials.** The instruments and materials used in Experiment 2b were identical to those used in Experiment 1. Experiment 2b had four conditions: visual, auditory, “sounding + visual,” and “simulated sounding + visual.” The visual, auditory, and “sounding + visual” conditions were the same as those in Experiment 2a. In the “simulate sounding + visual” condition, participants were asked to simulate the sounding condition via opening their mouth but not emitting any sound during the presentation of the white square, and closing their mouth when the white square disappeared; they then reproduced a subjectively equivalent presentation time by pressing the spacebar. As they only represented the white square during the reproduction, participants were asked to open and close their mouth at the onset and offset of the visual stimuli.

**Design and Procedure.** Experiment 2b adopted a one-factor within-subject design, with the dependent variables and analyses the same as those used in Experiment 2a. The procedure of Experiment 2b was identical to that of Experiment 2a, except that a new “simulate sounding + visual” condition was used.

## Results

**Accuracy Index.** Conducting the same analyses as in Experiment 2a, a repeated-measures ANOVA revealed a main effect of modality,  $F(3, 81) = 10.24$ ,  $p < .001$ ,  $\eta_p^2 = 0.28$ . *Post-hoc* analysis showed that the auditory ( $M = 0.11$ ), “sounding + visual” ( $M = 0.10$ ), and “simulate sounding + visual” ( $M = 0.12$ ) conditions were more accurate than the visual condition ( $M = 0.20$ ) at  $p < .001$ ,  $p < .001$ , and  $p < .01$ , respectively. No significant differences were observed among the three groups. These results indicate that auditory stimuli can improve visual-time perception through sounding. However, action plays an important role during sounding in terms of time perception (Figure 4).

**Variability in Reproduction.** Results also demonstrated a main effect of modality on the *SD* of reproduction,  $F(3, 81) = 11.97$ ,  $p < .001$ ,  $\eta_p^2 = 0.31$ . *Post-hoc* analysis showed that the auditory condition ( $M = 194.49$ ) was less variable than the visual ( $M = 257.97$ ), “sounding + visual” ( $M = 266.71$ ), and “simulate sounding + visual” ( $M = 283.70$ ) conditions at  $p < .01$ ,  $p < .001$ ,  $p < .001$ , respectively. As Figure 4 shows, there were no significant differences among the three groups. Similar to



**Figure 4.** Accuracy (left panel) and precision (right panel) of reproduction across auditory, visual, simulate sounding + visual and sounding + visual conditions.

*Note:* Error bars represent the standard error. The abbreviation “n.s.” means “not significant”, \*\* $p < .01$ , \*\*\* $p < .001$ .

Experiment 2a, these results indicate that auditory modality was less variable than visual modality. Moreover, the addition of auditory stimuli and actions did not affect reproductive variability.

According to the results of Experiment 2b, auditory stimuli and actions can increase visual time perception during sounding. However, as in the case of Experiment 2a, the effect was only manifested in accuracy and not in the precision of reproduction.

## Discussion

In Experiment 2b, we tested whether auditory stimuli or the action component improved visual-time perception through sounding. According to the accuracy index results, the “simulate sounding + visual” condition was as accurate as the “sounding + visual” condition, suggesting that the action component plays an important role in sounding. This aligns with previous studies in which perceived duration was overestimated during participants’ body movements (Kroger-Costa et al., 2013; Press et al., 2014; Sayalı et al., 2018). The mechanism underlying this phenomenon may be that the action increases the perceived duration by increasing the internal clock rate (Petruzzo et al., 2022; Sayalı et al., 2018; Wearden et al., 1999). Additionally, the process of simulating sounding may produce an internal sound, leading to more accurate time perception. It is worth noting that we did not require participants to produce or not produce an internal sound in the “simulate sounding + visual” condition. Participants were only asked to open their mouths when the visual stimuli were present, and close them when the visual stimuli were absent. However, previous research indicates that visual stimuli are automatically and involuntarily encoded in an auditory format during time perception (Guttman et al., 2005). Therefore, both action and auditory coding may cause more accurate time perception in the “simulate sounding + visual” conditions. Similar to Experiment 2a, the effect of sounding on visual time perception was not reflected in the *SD* of reproduction. Accordingly, the addition of auditory stimuli or actions does not improve the precision of temporal estimates. Nevertheless, the results of both Experiments 2a and 2b suggested that adding auditory stimuli via sounding may improve the accuracy of visual-time perception.

In view of the fact that imagining a sound involves a similar auditory coding process (Halpern & Zatorre, 1999; Herholz et al., 2008, 2009; Zatorre & Halpern, 2005), we tested whether imagining a sound improves visual time perception. As imagining a sound excludes actions, it follows that it can be used to test whether auditory coding is the key component in improving visual time perception.

## Experiment 3

Experiments 2a and 2b confirmed that adding auditory stimuli to visual time perception via sounding could improve timing accuracy. As sounding is not always applicable, it was necessary to adopt a more widely applicable method. Previous studies have shown that internally generated sounds have similar auditory processing, whereas imaginary sounds involve the auditory cortex (Halpern & Zatorre, 1999; Herholz et al., 2008, 2009; Zatorre & Halpern, 2005). Therefore, Experiment 3 tested whether visual-time perception was improved by imagining a sound when visual stimuli appeared. If the accuracy of time perception was higher in the “imagine sounds + visual” condition than in the visual condition, it would suggest that imagining a sound improves visual time perception and that auditory coding plays a key role in improving visual time perception.

## Method

**Participants.** A total of 29 participants (25 women,  $M_{\text{age}} = 21.38$ ,  $SD = 2.44$ ) participated in Experiment 3. The *a priori* power analysis was the same as that employed in Experiment 1.

Participants had normal or corrected-to-normal vision and no hearing problems. They also completed the same questionnaire as the participants of Experiment 1. Results showed low state anxiety ( $M \pm SD = 38.21 \pm 8.46$ ), low depression ( $M \pm SD = 5.79 \pm 4.84$ ), the PA score ( $M \pm SD = 26.83 \pm 7.73$ ), and the NA score ( $M \pm SD = 14.17 \pm 5.40$ ).

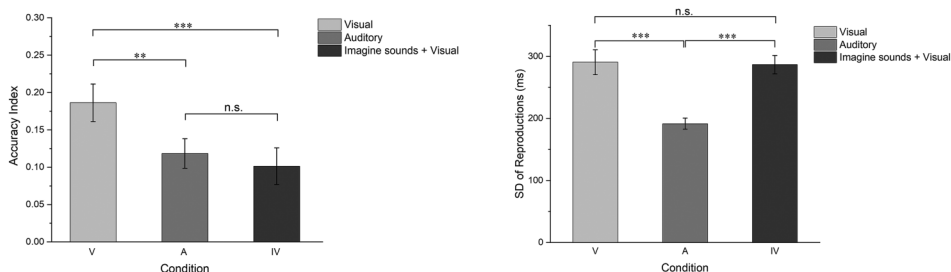
**Materials.** The instruments and materials used in Experiment 3 were identical to those used in Experiment 1. Experiment 3 comprised three conditions: visual, auditory, and “imagine sounds + visual.” The visual and auditory conditions were the same as those in Experiment 1. In the “imagine sounds + visual” condition, participants were asked to imagine a “beep” at the beginning of the white square presentation until it disappeared, and then reproduce the presentation time by pressing the spacebar. As in previous experiments, participants were also instructed to imagine a “beep” during the entire reproduction process.

**Design and Procedure.** Experiment 3 employed a one-factor within-subject design with the dependent variables and analyses as those in Experiment 2a. The procedure was identical to that in Experiment 2a, except that a new “imagine sounds + visual” condition was used.

## Results

**Accuracy Index.** Adopting the same analyses of Experiment 2a, repeated-measures ANOVA revealed the main effect of modality,  $F(2, 56) = 13.88$ ,  $p < .001$ ,  $\eta_p^2 = 0.33$ . Additionally, as predicted, *post-hoc* analysis showed that the “imagine sounds + visual” condition ( $M = 0.10$ ) was more accurate than the visual condition ( $M = 0.19$ ),  $t(28) = 4.72$ ,  $p < .001$ ; and that the auditory condition ( $M = 0.12$ ) was more accurate than the visual condition ( $M = 0.19$ ),  $t(28) = 4.00$ ,  $p < .01$ . However, we observed no difference between the “imagine sounds + visual” condition and auditory condition,  $t(28) = 1.06$ ,  $p = .87$  (Figure 5).

**Variability in Reproduction.** Results also revealed a main effect of modality on *SD* of reproduction,  $F(2, 56) = 25.38$ ,  $p < .001$ ,  $\eta_p^2 = 0.48$ . *Post-hoc* analysis showed that the auditory condition ( $M = 191.57$ ) was less variable than both the “imagine sounds + visual” condition ( $M = 286.74$ ),  $t(28) = 7.53$ ,  $p < .001$ , and the visual condition ( $M = 290.68$ ),  $t(28) = 5.52$ ,  $p < .001$ . However, as Figure 5 shows, there was no difference between the “imagine sounds + visual” and the visual conditions,  $t(28) = 0.24$ ,  $p = 1.00$ .



**Figure 5.** Accuracy (left panel) and precision (right panel) of reproduction across auditory, visual, and imagine sounds + visual conditions.

Note: Error bars represent the standard error. The abbreviation “n.s.” means “not significant”,  $**p < .01$ ,  $***p < .001$ .

According to the results of Experiment 3, auditory stimuli can be used to improve visual time perception by imagining sounds. As in the case of Experiments 2a and 2b, the effect was only reflected in the accuracy instead of the precision of reproduction.

## Discussion

Experiment 3 tested whether adding auditory stimuli to visual-time perception by imagining a sound improves timing accuracy. In accordance with our hypothesis, the results of the accuracy index showed that imagining a sound when visual stimuli appeared improved the visual time perception. This was consistent with the modality effects observed in Experiments 1, 2a, and 2b as well as findings of previous studies (Droit-Volet et al., 2007; Goldstone & Goldfarb, 1964; Plummer & Humphrey, 2009; Walker & Scott, 1981; Wearden et al., 1998), further supporting our initial hypothesis. Moreover, imagining a sound excludes the action component, suggesting that auditory coding plays a key role in improving visual time perception. However, imagining sounds did not decrease the *SD* of reproduction. As such, the results of Experiment 3 indicated that the addition of auditory stimuli via imagining sounds does not affect the precision of reproduction.

## General Discussion

Previous studies have demonstrated a modality effect on time perception (Droit-Volet et al., 2007; Goldstone & Goldfarb, 1964; Plummer & Humphrey, 2009; Walker & Scott, 1981; Wearden et al., 1998), with auditory stimuli typically judged more accurately and precisely than visual stimuli and found to dominate the perceived timing of audiovisual stimuli (Burr et al., 2009; Gori et al., 2012; Ortega et al., 2014; Walker & Scott, 1981). Therefore, this study sought to improve visual time perception using auditory superiority. Experiment 1 verified the modality effect through a reproduction task. Meanwhile, rather than relying on visual stimuli alone, Experiments 2a, 2b, and 3 added auditory stimuli to the time perception process via sounding or imagining a sound.

More specifically, Experiment 1 examined the accuracy and precision of time perception under visual, auditory, and audiovisual conditions. Results demonstrated that the auditory and audiovisual modalities were more accurate and precise than the visual modality, which is consistent with the results of previous studies (Bratzke & Ulrich, 2019; Plummer & Humphrey, 2009; Ulrich et al., 2006; Walker & Scott, 1981). The results of the modality effect imply that auditory superiority can be used to improve visual-time perception. Therefore, we hypothesized that the addition of auditory stimuli would improve visual time perception compared with viewing only visual stimuli. To test whether sounding could improve visual time perception, Experiment 2a required participants to make a “beep” sound when they saw the visual stimuli. The results showed that the accuracy of time perception was higher in the “sounding + visual” condition than the visual and auditory conditions. While verifying our hypothesis, this finding raised a new question. Based on previous research, we assumed that actions may play an important role during sounding (Anobile et al., 2020; Kroger-Costa et al., 2013; Petrizzo et al., 2022; Press et al., 2014; Sayah et al., 2018; Yokosaka et al., 2015). Therefore, Experiment 2b tested whether auditory stimuli or action components played an important role in sounding. More specifically, based on Experiment 2a, we added a new “simulate sounding + visual” condition that required participants to open and close their mouths at the onset and offset of the visual stimuli, respectively. Results suggested that the “simulate sounding + visual” and “sounding + visual” conditions had similar accuracy indices. In line with previous studies, this finding suggests that action improves time perception (Kroger-Costa et al., 2013; Press et al., 2014; Sayah et al., 2018). In addition to the action component, auditory coding may be involved in the “simulate sounding + visual” condition. Research indicates that visual stimuli tend to be unintentionally encoded in an auditory format during time

perception (Guttman et al., 2005), which means that both action and auditory coding may affect visual time perception. As such, one must be cautious when interpreting the effect of sounding on visual time perception.

While sounding could improve the accuracy of perception, it is not always applicable. Therefore, this study sought to use a more convenient and widely applied method than sounding. As previous studies suggest that imagined sounds also share an auditory coding process (Halpern & Zatorre, 1999; Zatorre & Halpern, 2005), we added auditory stimuli to time perception by using an imaginary rather audible sound in Experiment 3. This operation can also verify whether action or auditory coding plays a key role in improving visual time perception. Specifically, we required participants to imagine a beep when they saw the visual stimuli. The results indicated that the accuracy of time reproduction was higher in the “imagine sounds + visual” condition than in the visual condition. These findings confirm our initial hypothesis and suggest that whether the sound stimulus is audible or imaginary improves visual time perception. This also supports the hypothesis that auditory coding is a key component in improving visual time perception.

However, the addition of auditory stimuli did not affect reproduction precision. In Experiments 2a, 2b, and 3, the effects of sounding and imagining sounds on visual time perception were not reflected in the *SD* of the reproduction. These experiments thus confirmed that auditory estimates had smaller reproduction variability than visual estimates. According to the PA model, increased clock speed should decrease reproduction variability (Bratzke & Ulrich, 2019). Therefore, the variability during estimation should be smaller under sounding and imagining sound conditions. The unchanged *SD* of reproduction indicates that the variation in task-related behavior does not fully reflect the effects of the internal clock (Sayali et al., 2018). For example, Walker and Scott (1981) required participants to reproduce the perceived time of light, tone, or both light and tone by pressing a button. Demonstrating a main effect of modality on the mean response, their results indicated that tones and the simultaneous presentation of both light and tone were perceived to be longer than light. However, there was no main effect of modality on the standard deviations of the response. Meanwhile, to investigate the effect of motion on time perception, Sayali et al. (2018) and Kroger-Costa et al. (2013) required participants to perform a time-perception task while running or standing. Although they observed changes in reproduction times and shifts in the mean points of subjective equality, they did not observe any changes in variability during running. Therefore, the *SD* of reproduction may not be suitable for measuring the effects of auditory stimuli on visual time perception.

This study found that auditory stimuli were perceived more accurately and precisely than visual stimuli and that adding auditory stimuli improved visual time perception. The mechanism underlying these results aligns with the assumptions of both the PA model and the theory regarding the relative weight of auditory and visual stimuli in audiovisual conditions. According to the former, auditory stimuli should generate more pulses due to its faster pacemaker rate and capture attention more easily (Church, 1984; Gibbon et al., 1984; Meck, 1984; Mella et al., 2011; Penney et al., 2000, 2003; Treisman, 1963; Wearden et al., 1998, 2006). Meanwhile, the latter proposed auditory dominance over vision in time perception (Burr et al., 2009; Gori et al., 2012; Ortega et al., 2014; Walker & Scott, 1981). Thus, as noted, this study found that auditory stimuli were perceived more accurately and precisely than were visual stimuli in Experiment 1.

The results of this study also demonstrated that audiovisual stimuli were perceived more accurately and precisely than visual stimuli, indicating that auditory stimuli can be used to improve visual time perception. In this respect, Experiments 2a and 2b found that sounding improved visual time perception when the visual stimuli appeared. This finding confirms the application of the modality effect, because visual and auditory stimuli share a common psychological representation of time perception.

Results showed that additional auditory stimuli via sounding improved visual-time perception. However, both action and auditory coding may play an important role in the sounding process.

Experiment 3 found that imagining sounds had the same effect on visual-time perception, suggesting that the imagined sounds had similar auditory coding to real sounds and further demonstrating that auditory coding is an important factor in improving visual time perception. Previous studies have demonstrated that imaginary and audible sounds draw on similar neural mechanisms in the auditory cortex (Halpern & Zatorre, 1999; Herholz et al., 2008, 2009; Zatorre & Halpern, 2005).

Stimuli can exist in multiple sensory modalities. However, visual stimuli always dominate sensory processing, neglecting auditory stimuli (Gibson, 1933; Posner et al., 1976). For example, instead of hearing the wristwatch ticking, we perceive time by observing the movement of the hands. Similarly, when we wish to cross the road, we rely on our vision to observe the distance of the car from us rather than the sound of its engine. In terms of time perception, most events depend on visual stimuli. However, previous studies have indicated that visual modality is not accurate enough (Droit-Volet et al., 2007; Goldstone & Goldfarb, 1964; Walker & Scott, 1981; Wearden et al., 1998). This study demonstrated the superiority of the auditory modality, indicating that we can train participants to use auditory information to improve time perception. Single-sensory modality stimuli are also available. As such, we can use auditory information to improve time perception by adopting assistant methods, such as sounding or imagining a sound, to achieve more accurate time perception.

### Limitations

First, although we confirmed that auditory stimuli can improve visual time perception based on behavioral evidence, there is no neural evidence elucidating the underlying mechanism. Research shows that light stimuli are registered by the visual system, whereas sound stimuli are registered by the auditory system (Moore, 2002; Zihl & von Cramon, 1980). Behavioral data demonstrate audiovisual interactions in time perception, suggesting a connection between auditory and visual stimuli in the cerebral cortex. Therefore, researchers should consider using neural imaging methods to explore these underlying mechanisms.

Second, in Experiments 2a and 2b, we added auditory stimuli to the visual time perception via sounding, which invariably included an action component. The effect of sounding on visual time perception is confounded by the fact that the action component expands the time perception (Kroger-Costa et al., 2013; Sayalı et al., 2018; Yokosaka et al., 2015). In Experiment 3, we demonstrated that auditory coding was the key component in improving visual time perception. However, caution should be exercised when interpreting these results.

Third, we adopted a time-reproduction task to assess time perception. Some studies have observed a modality effect using time bisection tasks (Droit-Volet et al., 2007; Penney et al., 2000; Wearden et al., 2006) and verbal time estimation (Bschor et al., 2004; Wearden et al., 1998). Different measurement tools highlight different aspects of temporal processing (Cui et al., 2022). While the time reproduction task is a suitable method for measuring time perception (Plummer & Humphrey, 2009), further studies using other paradigms should be conducted to confirm these findings. Similarly, this study used the accuracy index and *SD* of reproduction as dependent variables to analyze the effects of sounding and imagining sounds on visual time perception, with results only indicating improvement in the former. Although the *SD* of reproduction represents the variability of temporal estimates used in related research (Bratzke & Ulrich, 2019), it may not be sensitive to the results of this study. Therefore, future research should explore whether other measures of temporal perception (e.g., bisection points and difference limen) are sensitive to the effects of sounding and imagining sounds.

Fourth, as this study used single stimuli to test time perception in different modalities, it lacks ecological validity. Accordingly, future studies should use more natural and representative stimuli to confirm the results of this study. For example, emotional pictures could be used to test the ecological validity of this study.

Finally, there is no specific organ for time sensing (Poidevin, 2004). Time perception is believed to be dependent on other sensory organs. In addition to visual and auditory modalities, time can be perceived using tactile modalities. This study only used auditory stimuli to improve visual time perception. However, other senses are also not sufficiently accurate. Therefore, future research should explore whether auditory stimuli can improve the accuracy of other senses.

## Conclusion

This study sought to improve visual-time perception using modality effects. Results showed that (1) auditory stimuli were perceived more accurately and precisely than visual stimuli, (2) sounding when visual stimuli appeared improved the accuracy of visual time perception, and (3) imagining a sound when visual stimuli appeared also improved the accuracy of visual time perception. However, neither sounding nor imagining sounds affected temporal precision. These results suggest that adding auditory stimuli to sensory processing can improve the accuracy of visual-time perception.

## Author Contribution(s)

**Shasha Wei:** Methodology; Resources; Software; Writing – original draft; Writing – review & editing.

**Yu Tian:** Conceptualization; Investigation; Methodology; Supervision; Writing – original draft; Writing – review & editing.

**Jiajin Yuan:** Conceptualization; Investigation; Project administration; Supervision; Writing – review & editing.

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