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Subliminal cues accompanied by action generate temporal expectancy and the role of supraliminal experience

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Abstract

Sensory events associated with motor actions are critical for perceptual calibration and motor control. Due to the stable temporal relationships between these events, individuals can anticipate the timing of one event based on another. While temporal expectancy is well-established for supraliminal stimuli (conscious cues) through temporal orienting, less is known about the role of subliminal cues generated by actions. Although subliminal stimuli are known to influence perception and behavior—specifically in forming spatial expectancies—their role in temporal expectancy remains unclear. Furthermore, evidence suggests that prior supraliminal experience may enhance the utilization of subliminal information. Integrating the conceptual link between space and time, the present study investigated whether individuals can form temporal expectancies based on action-generated subliminal stimuli and explored how supraliminal experience modulates this process. Our results indicate that participants do not form temporal expectancies through subliminal cues alone. Instead, the formation of such expectancy and transferred learning benefits upon target discrimination (i.e., orientation discrimination) depends on prior supraliminal experience with the association between the cue and the temporal onset of the subsequent target.

Keywords

sensorimotor system, subliminal perception, temporal expectancy, action-perception coupling

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Introduction

The execution of an action often triggers corresponding sensory events, known as the consequences of action. By perceiving these sensory consequences, individuals can understand and adapt to their external environment. These sensory outcomes serve as feedback that re-enters the nervous system, acting as input for subsequent cognitive processes or participating in the regulation of motor control (Coull et al., 2024; Schwartz & Pournaghdali, 2016). Thus, the execution of actions and the perception of their sensory consequences constitute a vital component of the interaction between an individual and their surroundings.

The efficient processing of sensory consequences facilitates motor control. For instance, when you reach into a refrigerator to grab a bottle of milk, if you perceive the weight to be greater than expected, you immediately exert more force to prevent the bottle from dropping and breaking. In this process, the sensory event—the weight of the bottle—is the result of the "grasping" action; it is simultaneously transmitted back to the brain as input to adjust the magnitude of force. In this manner, sensory consequences effectively calibrate motor control parameters, enabling more adaptive behavior. Masters et al. (2009) demonstrated this in a golf putting task by presenting participants with the visual sensory consequences of a rolling ball (Masters et al., 2009). In their task, one group received these visual results supraliminally, while the other received them subliminally. Results showed that participants in the supraliminal group performed better. Feedback resulting from action execution can modulate subsequent behavior, leading to more accurate motor control (Shadmehr et al., 2010).

Furthermore, the sensory consequences of an action also influence an individual's perception (Coull et al., 2024; Stetson et al., 2006). For instance, Stetson, Cui, Montague and Eagleman (2006) demonstrated a seminal illusion. They inserted a 100 ms delay between a participant's voluntary keypress and a visual flash. They found that the interval at which participants perceived the keypress and the flash as simultaneous increased over time (Stetson et al., 2006). This suggests that the perception of visual consequences reshapes the participant's subjective sense of time, a phenomenon known as the temporal recalibration effect (Stetson et al., 2006; Sugano et al., 2016). Rather than being static, our temporal perception is dynamically modulated by shifts in the temporal properties of action-induced sensory events to recalibrate our internal timeline (Sugano et al., 2012). While this temporal recalibration highlights how sensory consequences adjust subjective timing, it is also deeply intertwined with how the brain anticipates these events in time. This predictive modulation of time perception is closely aligned with the broader mechanisms of temporal expectation and temporal orienting. In temporal orienting paradigms and foreperiod (FP) tasks, the temporal predictability of a target stimulus—whether driven by explicit predictive cues or by the implicit passage of time during a preparatory interval (the FP)—allows individuals to direct their attention to specific instants in time, thereby optimizing behavioral and perceptual performance (Correa & Nobre, 2008; Coull & Nobre, 1998; Niemi & Näätänen, 1981; Nobre & van Ede, 2018). In the context of action-induced visual feedback, the predictability of a visual consequence following a motor command can act as a temporal marker. This temporal predictability enables the brain to actively orient attention and allocate cognitive resources to the expected moment of the sensory outcome, facilitating more efficient sensory processing and motor-sensory integration (Los, 2010; Miller-Goldwater et al., 2021). Consequently, sensory feedback serves not only as a mechanism for motor control but also as a critical temporal coordinate that guides the orienting of attention and preparation for subsequent events.

Temporal expectancy refers to the cognitive capacity to utilize endogenous and exogenous cues to predict the precise timing of upcoming events, a process fundamentally rooted in the implicit processing of temporal intervals (Coull, 2009; Coull et al., 2024; Coull & Nobre, 2008). By successfully anticipating an event's onset, individuals can optimize processing efficiency, resulting in accelerated reaction times (RTs) and heightened response accuracy. Within the sensorimotor system, this predictive ability allows for the accurate anticipation of the sensory consequences of actions, thereby strengthening motor control and facilitating adaptive perceptual recalibration (Shadmehr et al., 2010). Researchers typically investigate these mechanisms using two primary approaches: the FP paradigm, which measures how the interval between a warning signal and a target modulates readiness, and the temporal orienting paradigm, which employs symbolic cues to focus attention on specific points in time.

Sensory events triggered by actions are sometimes consciously perceivable, but at other times, they remain below the level of conscious awareness. Regardless, multiple sensory events triggered by the same action are always temporally correlated. In other words, the characteristics of action-induced outcomes across different sensory modalities are linked in time, even if these characteristics do not enter the actor's conscious awareness. By learning the temporal contingencies between sensory events, individuals can form expectancies regarding the consequences of their actions. Accurate expectancy of sensory outcomes allows for more efficient processing and can compensate for the inherent delays between actions and sensory events, making motor and perceptual calibration more precise (Shadmehr et al., 2010). When a sensory event serving as a cue appears supraliminally, it is easy for participants to learn the association between the cue and the future event (Pessiglione et al., 2008). Likewise, Barakat et al. (2013) found that after learning the temporal relationship between two paired stimuli, participants' detection of the second stimulus accelerated (Barakat et al., 2013). However, when sensory cues are presented subliminally, some studies have found that participants can still unconsciously form response patterns based on the association between cues and outcomes (Pessiglione et al., 2008). Then, one empirical research question is, when a subliminal cue appears as a consequence of an action, can individuals still acquire the temporal contingencies between these sensory events and form expectancies based on the temporal relationship between multiple action outcomes?

Because the shared metric of space and time is fundamentally geared toward facilitating motor action (Walsh, 2003), a critical question is whether these predictive spatiotemporal coordinates can be established and utilized implicitly, without conscious awareness of the triggering events. Research in cognitive psychology has increasingly demonstrated that attentional orienting and motor-sensory preparation are not restricted to conscious perception. Subliminal cues—even when rendered completely imperceptible through backward masking—can successfully capture spatial attention, trigger cognitive control settings, and prime motor systems to prepare for upcoming events (Ansorge et al., 2014; Hwang et al., 2021). This suggests that the predictive mechanisms of the brain can monitor action-consequence intervals at an unconscious, pre-reflective level. However, this subliminal processing does not occur in a vacuum; rather, it is highly sensitive to top-down influences and conscious task demands. According to the attentional sensitization model of unconscious processing, subliminal priming and predictive associations are actively modulated by conscious cognitive control states and the supraliminal context of the task (Kiefer & Martens, 2010; Kiefer et al., 2012). Thus, while the brain can automatically register spatial and temporal contingencies below the threshold of awareness, supraliminal experience dictates how flexibly these implicit predictions are integrated into our active motor-sensory models. Integrating this conceptual link between space and time, the present study investigated whether individuals can form temporal expectancies based on action-generated subliminal stimuli and explored how supraliminal experience modulates this process.

While research has established that spatial expectancies can be formed through subliminal cues even in the absence of conscious awareness (Lu et al., 2012; Uono et al., 2018), it remains unclear whether the temporal domain operates under similar constraints. Subliminal perception—where sensory outcomes influence behavior without reaching the threshold of consciousness—has been shown to facilitate task-set shifts and congruent priming effects (Reuss et al., 2015). However, the efficacy of subliminal processing may be contingent upon prior supraliminal exposure. As Faivre et al. (2014) suggest, conscious encounters with stimuli may be a prerequisite for the brain to integrate and utilize information that subsequently falls below the threshold of awareness (Faivre et al., 2014).

The present study hence aims to bridge these theoretical gaps by investigating whether individuals can establish temporal expectancies for supraliminal events based on the subliminal sensory consequences of their actions. Specifically, we explore whether the formation of these expectancies is an autonomous process or one that requires modulation by prior supraliminal experience. By examining the interplay between action-induced feedback and conscious learning, this research seeks to clarify the boundaries of unconscious temporal processing and its role in sensorimotor integration.

Methods

In this study, participants' voluntary keypresses generated Gabor patch stimuli. The participant-s'task was to determine whether the orientation of the target Gabor patch was tilted clockwise or counter-clockwise relative to the vertical axis. The research comprised three experiments (with an additional control experiment following reviewer's suggestion). In Experiment 1, a subliminal cue was presented following each keypress, followed by a variable time interval before the target appeared. Different cues predicted different interval lengths, allowing us to investigate whether individuals can form temporal expectancies for supraliminal outcomes based on the subliminal sensory consequences of their actions.

Experiment 2 followed the same basic procedure as Experiment 1; however, the cues following the keypresses were presented both supraliminally and subliminally. This design was used to examine whether prior supraliminal experience with the temporal relationship between the cue and the target facilitates the formation of temporal expectancies based on subliminal cues. Experiment 3 served as a control for both previous experiments. In this version, no cues were presented after the keypresses, allowing us to evaluate the influence of general practice effects on task performance. Finally, in Experiment 4, to determine whether geometric cues were processed consciously, we conducted a forced-choice awareness test mirroring the structure of the main experiment. Participants viewed briefly presented, masked cues, and were required to identify them, regardless of their subjective level of awareness.

Participants

Sixteen participants (4 males) were recruited for Experiment 1, 16 (4 males) for Experiment 2. Eighteen participants (8 males) were recruited for Experiment 3; one participant was excluded for failing to reach the 75% accuracy criterion during the practice phase, leaving seventeen participants (8 males) in the final sample. In Experiment 4, 16 participants (10 female) attended a forced-choice awareness test. All participants were between 18 and 30 years of age. Upon completion of the sessions, participants were compensated at a rate of 40 CNY per hour.

To evaluate the adequacy of our sample sizes retrospectively without relying on uninformative post-hoc power, we conducted a sensitivity power analysis using G*Power 3.1 (Faul et al., 2007) for our mixed-design ANOVA. Given a sample size of 16 participants, an alpha level of 0.05, and a desired statistical power of 0.80 (with 2 groups and 6 measurements), the analysis indicated that our design is sufficiently sensitive to detect a minimum effect size of $f = 0.27$ (equivalent to a partial η^2 of approximately 0.067). Because the critical effect sizes observed in our experiments consistently exceeded this threshold, our sample size of 16–17 participants provided adequate statistical power to detect the temporal expectancies of interest.

Apparatus and Stimuli

Stimuli were exclusively visual, programed in MATLAB, and presented on a 27-inch monitor with a 100 Hz refresh rate (ASUS PG278QR monitor; NVIDIA GeForce GTX 1080 Ti graphics card). The target was a Gabor patch (1.4°×1.4°) with 25% contrast, tilted at a specific angle relative to the vertical axis. This angle varied across trials according to a truncated normal distribution centered on the participant's 75% detection threshold ($\sigma = 0.5°$, range: [threshold − 0.5°, threshold + 0.5°]). Across all trials and participants, the observed tilt angles were 1.55° ± 1.08° (range: 0.01°–4.31°) in Experiment 1, 1.09° ± 0.58° (range: 0.002°–2.31°) in Experiment 2, and 1.29° ± 0.62° (range: 0.03°–2.64°) in Experiment 3.

Two shapes served as cues: a dark gray square (1.4°×1.4°) and a circle (1.4° diameter). There was a stable temporal contingency between the cue and the target. Additionally, a circular checkerboard pattern was used as a masking stimulus.

Experiment 1: Subliminal Cues

Experiments were conducted in a quiet, dimly lit environment. Participants were seated 65 cm from the screen with their heads stabilized by a chin rest while fixating on the center of the display. On a dark gray background, a fixation cross was first presented for 500 ms. After the fixation disappeared, participants were required to perform a voluntary keypress within 2.5 s.

A dark gray geometric cue, serving as the sensory feedback for the voluntary action, appeared 30–50 ms post-keypress. The cue was presented for only 15 ms. A masking stimulus followed immediately and refreshed every two frames (20 ms) until the target appeared. The time interval between the onset of the cue and the target—referred to here as the FP—was set at 600, 800, 1000, 1200, 1400, 1600, or 1800 ms.

Trials with intervals of 800 ms and 1600 ms each accounted for 45% of each block, while the remaining 10% were distributed equally among the other five interval levels. We designated 800 ms and 1600 ms as peak intervals and the other levels as non-peak intervals. Crucially, a mapping existed between the two geometric cues and the two peak intervals. For half of the participants, the circular cue was paired with the short peak interval and the square cue with the long peak interval; for the other half, this mapping was reversed.

The target disappeared after 100 ms, followed by a blank screen while awaiting a response. Participants were tasked with judging whether the target's orientation was tilted clockwise or counter-clockwise relative to the vertical. If a response exceeded 2 s, the trial terminated; if the RT exceeded 1 s, a "Too Slow" warning was displayed on the screen (Figure 1).

Each block consisted of 82 trials, with the circular and square cues each appearing in half of the trials (41 trials each). Among the 41 trials featuring the circular cue, 36 trials utilized a cue-target interval of 800 ms (the short peak), while the remaining five non-peak intervals (600, 1000, 1200, 1400, and 1800 ms) occurred once each. Similarly, for the 41 trials featuring the square cue, the long peak interval (1600 ms) occurred 36 times, with each other non-peak interval occurring once.

Participants first completed a threshold measurement to determine the 75% accuracy level for target orientation. Threshold was measured using the QUEST adaptive Bayesian procedure (Watson & Pelli, 1983), with an initial estimate of 2.27° and a prior standard deviation of 2°, targeting 75% correct over 50 trials. Tilt angles in the main experiment were drawn from a truncated normal distribution centered on each participant's individual threshold ($\sigma = 0.5°$, range: [threshold − 0.5°, threshold + 0.5°]). Following threshold measurement, participants completed a practice session. The practice session followed the same procedure as the formal experiment, except that no geometric cues were presented after the keypress. This session included four trials for each of the seven interval levels, totaling 28 trials. Participants were required to reach an accuracy of at least

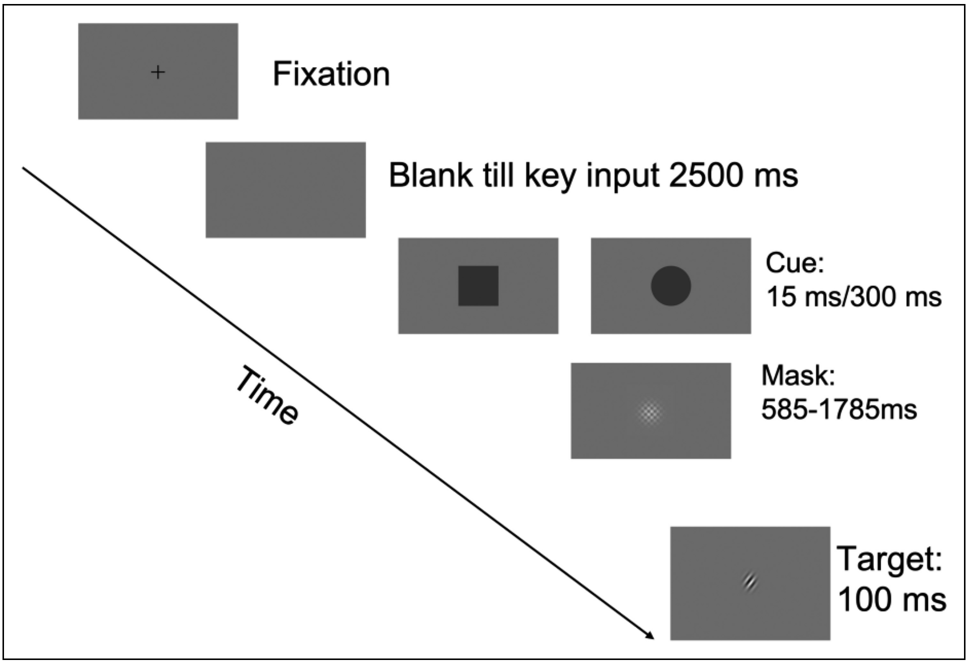

Figure 1. Experimental flowchart. After the fixation point disappears, participants must provide an active keypress within 2.5 s. Following the response, after a 30–50 ms interval, participants receive either a supraliminal cue (presented for 300 ms) or a subliminal cue (presented for 15 ms). A masking stimulus then replaces the cue and remains on screen until the target appears. Participants are required to judge the direction of the target as quickly as possible.

75% before proceeding to the formal experiment. The inter-trial interval was randomly sampled from a uniform distribution between 1000 and 1200 ms. Feedback on response accuracy was provided during the practice session but withheld during the formal experiment.

The formal experiment was divided into two phases: Learning and Testing.

1. Learning Phase: Consisted of two blocks where participants learned the temporal contingencies between cues and targets (Old Mapping).
2. Testing Phase: Consisted of four blocks in which all cues were presented subliminally. In the first two blocks of this phase, the temporal mapping remained identical to the learning phase (Old Mapping); in the final two blocks, the cue-target mapping was reversed (New Mapping).

Results for Experiment 1

For all data, trials with RTs less than 100 ms and greater than 1000 ms were excluded to calculate accuracy rates. We then calculated the RTs for trials in which participants made correct judgments.

In Experiment 1, participants' judgment accuracy rates and RTs at different prior time levels across blocks are shown in Table 1. First, we conducted a repeated-measures ANOVA with block order (1–6) and prior time (short peak/long peak) as within-subject factors to examine whether there was a general learning effect. For response accuracy, the main effect of block order was not significant ($F(3.14, 47.11) = 1.087$, $p = .366$, $\eta_p^2 = .068$), the main effect of prior time was not significant

Table 1. Accuracies and RTs (ms) for Experiment 1. Values in parentheses represent standard deviations of the means.

		Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
Short peak	Accuracy	0.819 (0.10)	0.807 (0.12)	0.809 (0.12)	0.820 (0.10)	0.781 (0.14)	0.783 (0.14)
	Reaction time	625 (63)	602 (60)	592 (54)	607 (43)	596 (63)	587 (46)
Long peak	Accuracy	0.803 (0.12)	0.829 (0.11)	0.770 (0.14)	0.794 (0.11)	0.795 (0.12)	0.803 (0.11)
	Reaction time	630 (52)	600 (43)	599 (53)	586 (29)	582 (63)	575 (53)

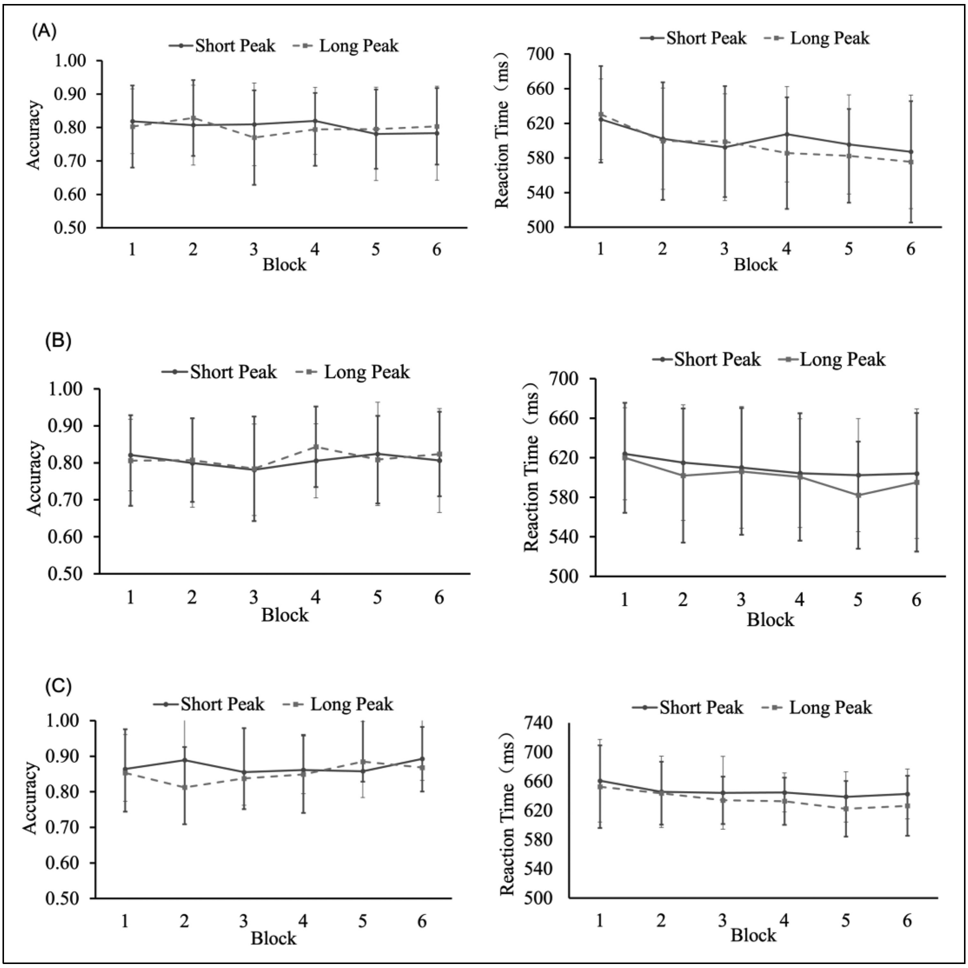

Figure 2. Participants' accuracy and reaction times across different blocks. (A) Data for the subliminal learning experimental group in Experiment 1; (B) data for the supraliminal learning group in Experiment 2; and (C) data for the control group in Experiment 3.

($F(1, 15) = .371$, $p = .551$, $\eta_p^2 = .024$), and the interaction between the two was also not significant ($F(3.08, 46.12) = .758$, $p = .526$, $\eta_p^2 = .048$). For response time, the main effect of block order was not significant ($F(2.85, 42.75) = 1.790$, $p = .166$, $\eta_p^2 = .107$), the main effect of prior time was not significant ($F(1, 15) = 3.594$, $p = .077$, $\eta_p^2 = .193$), and the interaction between the two was also not significant ($F(5, 75) = .971$, $p = .425$, $\eta_p^2 = .061$). Neither judgment accuracy nor response time showed significant learning effects at any prior time level (see Figure 2A).

Each of the three conditions—subliminal learning, old-matched subliminal test, and new-matched subliminal test—comprised two blocks. We merged the data from the two blocks within each condition. Conducting a repeated-measures ANOVA on the merged data with cue type (subliminal learning/subliminal old-matched/subliminal new-matched) and prior time duration (short peak/long peak) as within-subject factors, and the match between cue and time duration as a between-subjects variable, we found that the match between cue and prior time duration had no significant effect on either accuracy or RT (accuracy: $F(1, 14) = .017$, $p = .897$, $\eta_p^2 = .001$; RT: $F(1, 14)$

$= 3.858$, $p = .070$, $\eta_p^2 = .216$). Therefore, we collapsed the data across different matching conditions and performed another repeated-measures ANOVA on the merged data with cue type and prior time duration as within-subject factors. For response accuracy, the main effect of cue type was not significant ($F(2, 30) = .267$, $p = .767$, $\eta_p^2 = .017$), the main effect of prior time duration was not significant ($F(1, 15) = .371$, $p = .551$, $\eta_p^2 = .024$), and the interaction between the two was also not significant ($F(2, 30) = .476$, $p = .626$, $\eta_p^2 = .031$). To further evaluate the strength of evidence for the null effect of FP within specific cue-type phases, we conducted paired-samples *t*-tests with Bayes factors comparing accuracy in the short peak versus long peak conditions separately within the subliminal learning phase and the old-matched subliminal test phase. In the subliminal learning phase, no difference was found ($t(15) = 0.182$, $p = .858$, *Cohen's* $d = 0.046$, $BF_{01} = 3.858$), providing moderate evidence for the null hypothesis. In the old-matched subliminal test phase, the comparison was inconclusive ($t(15) = -1.019$, $p = .324$, *Cohen's* $d = -0.255$, $BF_{01} = 2.501$), as the Bayes factor did not reach the conventional threshold ($BF_{01} > 3$) for either hypothesis. For RT, the main effect of cue type was not significant ($F(2, 30) = 2.050$, $p = .146$, $\eta_p^2 = .120$), the main effect of prior time duration was not significant ($F(1, 15) = 3.549$, $p = .077$, $\eta_p^2 = .191$), and the interaction between the two was also not significant ($F(2, 30) = 1.839$, $p = .177$, $\eta_p^2 = .109$).

Since the cue type had no impact on accuracy or RT and no interaction effects were found, we hypothesize that participants did not form temporal expectations for subsequent events based on the subliminal sensory outcomes of their actions. Furthermore, the FP duration did not significantly influence performance, suggesting that participants failed to internalize the regularity or peak of the timing intervals; consequently, they did not develop temporal expectations as is typically observed in traditional FP paradigms. We suspect this failure to effectively utilize subliminal cues may be linked to task difficulty and lack of prior experience: judging the orientation of Gabor patches is resource-intensive and likely interfered with expectation formation, while the abstract geometric cues lacked the real-world associations typical of daily life. Given that previous research suggests supraliminal experience is often a prerequisite for the effective use of subliminal cues, In Experiment 2, we required participants to learn the temporal associations at a conscious level to investigate whether this prior learning facilitates the utilization of subliminal information during task execution.

Experiment 2: Supraliminal Cues

The core components of Experiment 2 were identical to Experiment 1, with one critical distinction: during the Learning Phase, the cues following the participant's keypress were presented supraliminally. Specifically, the cues were displayed for 300 ms before the onset of the mask. The duration of the intervals between cue onset and target onset remained consistent with those used in Experiment 1.

Results for Experiment 2

The accuracy and RTs for each block across different FP levels in Experiment 2 are presented in Table 2. In this experiment, we aimed to examine the influence of supraliminal experience on the formation of temporal expectations for future events based on the subliminal sensory outcomes of actions. Learning effects were analyzed using a repeated-measures ANOVA on RTs and accuracy, with block order (1–6) and FP duration (short peak/long peak) as within-subject factors. Regarding judgment accuracy, there were no significant main effects for block order ($F(2.43, 36.42) = .704$, $p = .527$, $\eta_p^2 = .045$) or FP duration ($F(1, 15) = .445$, $p = .515$, $\eta_p^2 = .029$), nor was there a significant interaction effect ($F(5, 75) = 1.610$, $p = .168$, $\eta_p^2 = .097$). For RTs of correct judgments, the main effect of block order was significant ($F(5, 75) = 4.665$, $p = .001$, $\eta_p^2 = .237$), while

Table 2. Accuracies and RTs (ms) for Experiment 2. Values in parentheses represent standard deviations of the means.

		Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
Short peak	Accuracy	0.821 (0.07)	0.799 (0.10)	0.781 (0.11)	0.805 (0.09)	0.824 (0.09)	0.806 (0.09)
	Reaction time	624 (47)	615 (59)	610 (62)	604 (55)	602 (57)	604 (66)
Long peak	Accuracy	0.806 (0.11)	0.807 (0.08)	0.784 (0.09)	0.843 (0.06)	0.809 (0.09)	0.824 (0.09)
	Reaction time	620 (56)	602 (68)	606 (64)	601 (64)	582 (54)	595 (70)

the main effect of FP duration was not ($F(1, 15) = 2.055$, $p = .172$, $\eta_p^2 = .120$); however, the interaction between the two was significant ($F(5, 75) = 4.180$, $p = .002$, $\eta_p^2 = .218$). All post-hoc comparisons were conducted using Fisher's LSD method. Post-hoc tests revealed that in the short peak condition, RTs in the first block were marginally significantly longer than in the third block ($p = .064$), with no other significant inter-block differences (ps > .094). In the long peak condition, RTs in the second, fourth, fifth, and sixth blocks were significantly shorter than in the first block (ps < .035), while no other significant differences were found between the remaining blocks (ps > .317). While accuracy did not show evidence of a practice effect, the RT data indicated a clear practice effect in the long peak condition, characterized by a gradual decrease in RT over time. Although we cannot definitively rule out a practice effect in the short peak condition—as this condition is where temporal orienting effects are most likely to occur—it is possible that changes in cue types offset the observable impact of practice.

To examine whether temporal expectations established based on the temporal relationship between supraliminal cues and targets could transfer to subliminal cues, we collapsed the data from the two blocks across the three conditions of supraliminal learning, old-matched subliminal test, and new-matched subliminal test. Using repeated-measures ANOVA with cue type (supraliminal cue/subliminal old-matched/subliminal new-matched) and prior time duration (short peak/long peak) as within-subject factors, and the match between cue and time duration as a between-subjects variable, we analyzed participants' RTs and accuracy (Figure 3). The match between cue and time duration had no significant effect on either accuracy or RT (accuracy: $F(1, 14) = .078$, $p = .785$, $\eta_p^2 = .006$; RT: $F(1, 14) = .001$, $p = .970$, $\eta_p^2 = .001$). Therefore, we collapsed the data across different cue and prior time duration matching conditions and performed another repeated-measures ANOVA on accuracy and RT with cue type and prior time duration as within-subject factors.

For accuracy in judging Gabor orientation: the main effect of cue type was marginally significant ($F(2, 30) = 3.116$, $p = .059$, $\eta_p^2 = .172$), the main effect of prior time duration was not significant ($F(1, 15) = 1.164$, $p = .298$, $\eta_p^2 = .072$), and the interaction between the two was significant ($F(2, 30) = 3.553$, $p = .041$, $\eta_p^2 = .192$). Post-hoc tests indicated that changes in cue type had no significant effect on accuracy in either the short peak or long peak conditions (ps > .131). Under the supraliminal cue and subliminal new cue conditions, accuracy did not differ significantly across prior time duration levels (ps > .404). When the cue was a subliminal old cue, accuracy was significantly higher in the short peak condition than in the long peak condition ($p = .026$). If temporal expectations had not been successfully established, we would expect accuracy in the short peak condition to be lower than or comparable to that in the long peak condition. The actual results contradict this hypothesis; therefore, this dissociation in accuracy may reflect that participants transferred the learned relationship between cues and prior time durations, acquired through supraliminal cues, to subliminal cues.

For RT in making judgments: the main effect of cue type was significant ($F(2, 30) = 9.032$, $p = .001$, $\eta_p^2 = .376$). Participants showed significantly longer RTs in the supraliminal cue condition compared to both the subliminal old cue ($p = .027$) and subliminal new cue ($p = .006$) conditions, but RTs did not differ significantly between the two subliminal conditions ($p = .669$). Since the experimental order was fixed as supraliminal cue condition, subliminal old cue condition, and then subliminal new cue condition, the changes in RT likely reflect practice effects across the task. The main effect of prior time duration was not significant ($F(1, 15) = 3.095$, $p = .099$, $\eta_p^2 = .171$), and the interaction between the two factors was not significant ($F(2, 30) = 2.058$, $p = .145$, $\eta_p^2 = .121$). Post-hoc tests revealed no significant differences in RT across prior time duration levels in the supraliminal cue and subliminal old cue conditions (ps > .219). When the cue was a subliminal new cue, RT was significantly longer in the short peak condition than in the long peak condition ($p = .015$). That is, when the previously learned relationship between cues and prior time durations was disrupted, the pattern of RTs across different prior time duration levels changed, specifically

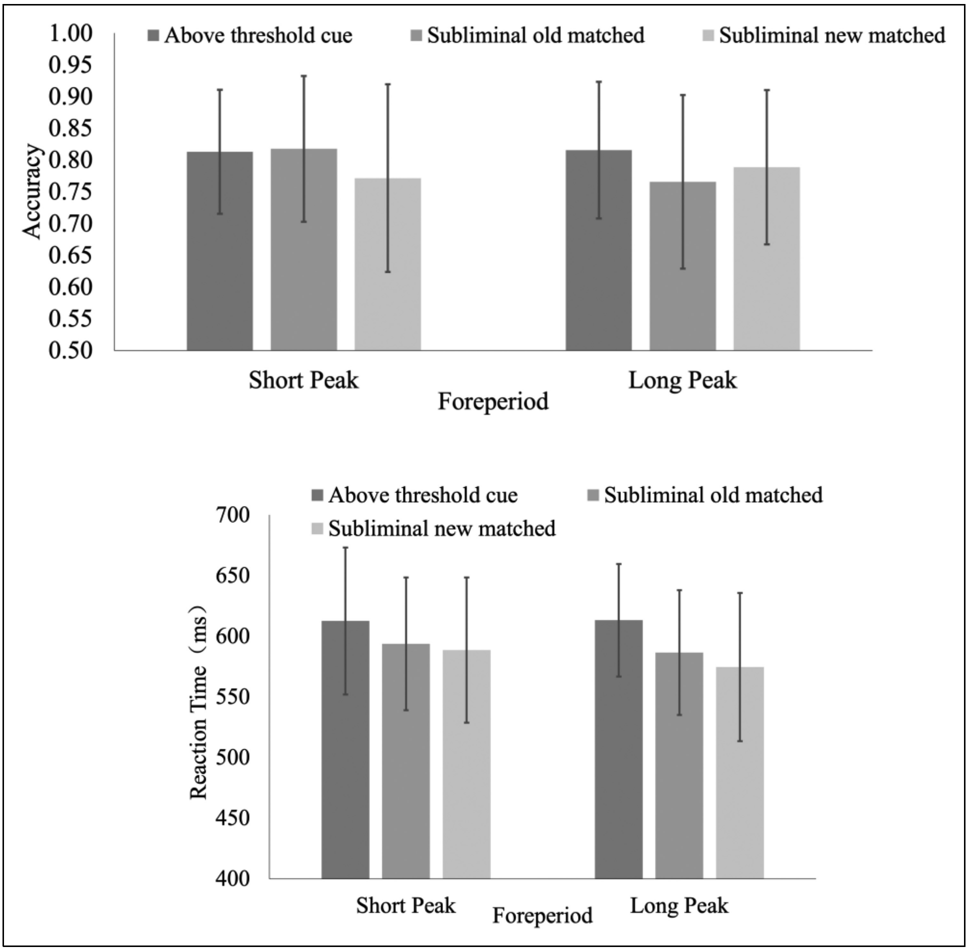

Figure 3. Participants' accuracy (up) and reaction times (down) across different foreperiod levels and cue types in Experiment 2.

manifesting as increased RT in the short peak condition, suggesting that participants may have acquired the relationship between cues and prior time durations to some extent.

Experiment 3: Control Experiment Without Cues

Experiment 3 served as a control experiment. In this version, no cues were presented during either the Learning Phase or the Testing Phase. All other experimental parameters remained identical to those in Experiment 1.

Results for Experiment 3

In Experiment 3, participants' judgment accuracy rates and RTs across blocks at different prior time levels are shown in Table 3. We conducted repeated-measures ANOVAs on accuracy and RT with block order (1–6) and prior time (short peak/long peak) as within-subject factors. For accuracy, the main effect of block order was not significant ($F(2.70, 43.24) = 1.257$, $p = .300$, $\eta_p^2 = .073$), the main

Table 3. Accuracies and RTs (ms) for Experiment 3. Values in parentheses represent standard deviations of the means.

		Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
Short peak	Accuracy	0.826 (0.10)	0.841 (0.11)	0.828 (0.11)	0.841 (0.09)	0.820 (0.13)	0.833 (0.12)
	Reaction time	640 (69)	631 (66)	629 (58)	633 (46)	631 (65)	620 (54)
Long peak	Accuracy	0.843 (0.19)	0.853 (0.18)	0.835 (0.19)	0.782 (0.21)	0.916 (0.13)	0.732 (0.33)
	Reaction time	620 (101)	586 (114)	630 (40)	629 (67)	632 (68)	592 (88)

effect of prior time was not significant (F(1, 16) = 0.060, p = .809, η_p^2 = .004), but the interaction between the two was significant (F(3.42, 54.67) = 2.693, p = .048, η_p^2 = .144). Simple effects analysis revealed that in block 5, accuracy was significantly higher in the long peak condition than in the short peak condition (p = .014); no significant differences between conditions were found in any other block (ps > .117). For RT, the main effect of block order was not significant (F(3.26, 45.60) = 1.427, p = .245, η_p^2 = .093), the main effect of prior time was not significant (F(1, 14) = 3.081, p = .101, η_p^2 = .180), and the interaction between the two was also not significant (F(3.16, 44.21) = 1.187, p = .327, η_p^2 = .078). These results indicate that participants' accuracy and RT did not show significant practice effects overall during the course of the experiment, consistent with the findings of Experiment 1. To quantify the strength of evidence for this null effect, we additionally conducted a Bayesian paired-samples t-test comparing accuracy in the short peak versus long peak conditions collapsed across all six blocks. No difference was found (t(16) = 0.246, p = .809, *Cohen's d* = 0.060, BF_{01} = 3.909), providing moderate evidence in favor of the null hypothesis that participants' accuracy did not differ as a function of FP duration in the absence of any cue.

Cross-Experiment Comparison

We examined whether the patterns of accuracy and RT data across the three experiments differed over time. In Experiment 3, we merged the data from Blocks 1 and 2, Blocks 3 and 4, and Blocks 5 and 6, yielding three segments. These three segments corresponded temporally to the three different experimental stages across the three cue-type levels in Experiments 1 and 2. We conducted a repeated-measures ANOVA on RT and accuracy with experimental stage (Part 1/Part 2/Part 3) and prior time (short peak/long peak) as within-subject factors, and experimental condition (Experiment 1: subliminal learning group/Experiment 2: supraliminal learning group/Experiment 3: control group) as a between-subjects factor.

For judgment accuracy, no significant main effects or interactions were found (all ps > .674). The three-way interaction of experimental stage × prior time × experimental condition was not significant (F(4, 90) = 0.586, p = .674, η_p^2 = .025). Post-hoc paired comparisons revealed no significant differences between short peak and long peak conditions within any Part for any experimental group (all ps > .324).

For RT, the main effect of experimental stage was significant (F(2, 90) = 4.137, p = .019, η_p^2 = .084) (Figure 4). Post-hoc tests indicated that RT in Part 1 was not significantly different from Part 2 (p = .544), but was significantly longer than Part 3 (p = .013), and Part 2 was also significantly longer than Part 3 (p = .021), suggesting a practice effect that emerged in the later stage of the experiment. The main effect of prior time (F(1, 45) = 2.380, p = .130, η_p^2 = .050) and the interaction of experimental stage × prior time (F(2, 90) = 1.440, p = .242, η_p^2 = .031) were not significant. The three-way interaction of experimental stage × prior time × experimental condition showed a marginal trend (F(4, 90) = 2.113, p = .086, η_p^2 = .086). No other significant effects were found.

Experiment 4: Awareness Measurement

To assess whether the geometric cues were processed consciously, a forced-choice awareness test was conducted with 16 participants (6 male, 10 female) using the same trial structure as the main experiment. On each trial, a geometric cue (circle or square) was presented for 15 ms and immediately followed by a mask. Participants subsequently completed the primary task and then identified the cue (circle/square) on every trial, regardless of subjective awareness. Each participant completed 164 trials (two blocks of 82 trials), with both cue types presented equally often.

At the group level, mean shape discrimination accuracy was 0.549 (SD = 0.130), which did not differ significantly from chance (0.5), t(15) = 1.522, p = 0.149, *Cohen's d* = 0.381. Signal detection

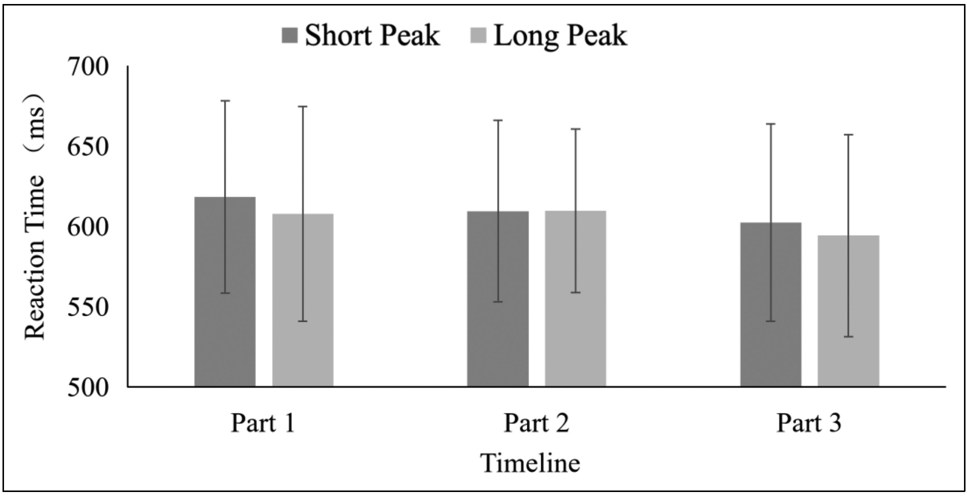

Figure 4. Reaction times for all participants across different experimental stages and foreperiod levels.

analysis further showed a mean sensitivity of d' = 0.345 (SD = 0.734), which was not significantly different from zero, $t(15) = 1.878$, $p = 0.080$, *Cohen's d* = 0.470. Bayesian analysis yielded $BF_{01} =$ 1.497 ($BF_{10} = 0.668$), indicating inconclusive evidence regarding the null hypothesis. Performance was comparable across cue types, with mean accuracies of 0.544 (SD = 0.214) for circle cues and 0.553 (SD = 0.185) for square cues.

Taken together, these results suggest that, at the group level, participants did not reliably discriminate the geometric cues above chance, although the Bayesian evidence was not decisive. This supports the premise that conscious access to the cues was limited under the current masking procedure.

General Discussion

With four experiments, we demonstrated that participants can form temporal expectations based on the supraliminal sensory consequences of actions, and that such temporal expectations can transfer to subliminal sensory consequences; however, subliminal sensory consequences cannot directly form temporal expectations.

In Experiment 1, the temporal relationship between subliminal cues and subsequent events could not be learned by participants, indicating that participants could not directly form expectations based on the subliminal sensory consequences of actions. This null effect was firmly supported by our complementary Bayesian analysis; specifically, the Bayes factor for the subliminal learning phase ($BF_{01} = 3.858$) provided moderate evidence in favor of the null hypothesis, confirming a genuine absence of temporal learning under purely subliminal conditions. Although the Bayes factor in the subsequent old-matched subliminal test phase ($BF_{01} = 2.501$) fell within the statistically inconclusive range, the overall pattern consistently demonstrates that temporal contingencies cannot be robustly internalized or transferred without conscious awareness. Although previous research has shown that participants can make stimulus-response mode task switches expected by the experimenter based on subliminal cues (Reuss et al., 2011), other studies have pointed out that participants only use subliminal cues when the subliminal stimulus is task-relevant (Gayet et al., 2014). When information provided by subliminal cues is task-relevant, participants are more likely to utilize the information contained in subliminal cues. However, in our experiment, despite the stable temporal association between subliminal cues and the target that could help participants anticipate when the target would appear, participants did not form temporal expectations based on subliminal cues. This may be related to our task. In our design, participants' task was simply to make correct judgments about the target as quickly as possible. Although this implicitly included the requirement to develop certain expectations about the target to reduce RT, this requirement was not direct. Participants likely did not adopt, or did not consistently adopt, a strategy of anticipating when the target would appear during task execution, and there was no direct measure of the accuracy of participants' expectations. If participants did not attempt to predict when the target would appear, the relationship between subliminal cues and participants' orientation judgment task would be weakened, reducing the likelihood of their utilization and ultimately failing to influence participants' task performance.

Second, whether temporal orienting effects can be successfully formed is also related to task difficulty. Correa et al. (2004) attempted to establish temporal orienting effects by associating supraliminal abstract geometric shapes with specific prior times. In a simple detection task, participants could form temporal expectations about the target based on abstract geometric cues; however, they could not form temporal expectations in a discrimination task. Correa et al. interpreted this as interference between the process of target-response matching and the establishment of temporal orienting (Correa et al., 2004). In their discrimination task, the targets were two different English letters, and participants reported which letter they saw by pressing different keys. Correa et al. argued that the letter-key matching occupied certain cognitive resources, making temporal orienting establishment more difficult. They then successfully elicited temporal orienting effects in the discrimination task by reducing the difficulty of target-response matching and using more intuitive cues to decrease the resources required for the task and temporal expectation establishment (Correa et al., 2005). In our experiment, participants' task was to judge the orientation of a Gabor stimulus—pressing the left key when the target was tilted counter-clockwise relative to vertical and the right key when tilted clockwise. The target-response matching method in our experiment was more intuitive than in Correa et al.'s experiment; however, judging the orientation of Gabor stimuli consumes considerable cognitive resources, thereby interfering with the formation of temporal orienting effects, which may be why we did not observe the establishment of temporal expectations. However, some researchers argue that when a task is too simple, the information contained in subliminal cues may be redundant and therefore not utilized. Task difficulty and the level of cognitive resource occupation are likely important factors influencing whether subliminal information is used, but there is currently no consistent conclusion.

Furthermore, compared with Correa et al.'s research, the cognitive resource consumption of Gabor stimulus orientation judgment is concentrated in the perceptual processing stage. Preparation for responding to the target can be divided into perceptual preparation and motor preparation. Some studies using the FP paradigm have indicated that participants' temporal expectations primarily facilitate the motor preparation process (Thomaschke et al., 2011a), and neuroimaging research has found that temporal orienting effects are related to activation in the prefrontal cortex and supplementary motor area (Coull, 2009). This partly explains why temporal orienting effects are larger in simple detection tasks than in discrimination tasks. Therefore, the motor preparation component may be more susceptible to the influence of temporal expectations. Here we used a discrimination task, and participants' primary processing load was concentrated in the perceptual processing stage. The lack of difference in participants' task performance between subliminal old cue and subliminal new cue conditions may be a result of the greater difficulty in influencing perceptual preparation by temporal expectations.

In Experiment 2, the match between cues and prior times had different effects on judgment accuracy and RT. For accuracy, in the subliminal old-match stage, accuracy in the short peak condition was higher than at other prior time levels, reflecting some improvement in task performance in the short peak condition. For RT, in the subliminal new-match stage, RT in the short peak condition was significantly longer than at the other two prior time levels, indicating that violating temporal expectations resulted in increased RT. Integrating these results, although there were no significant differences in task performance across prior time levels during the supraliminal cue stage, when cues were presented subliminally, the influence of temporal expectations on task performance was still manifested, and both effects appeared in the short peak condition. This is consistent with previous experimental results (Correa et al., 2004; Thomaschke et al., 2011b). In the long peak condition, when the target does not appear, the probability of target occurrence gradually increases over time. Even if participants expect the event to occur at the short peak moment, as time passes, participants can reorient their temporal attention to the long peak moment and re-prepare for the target response; therefore, temporal orienting effects did not influence participants' task performance in the long peak condition.

In the supraliminal condition, neither accuracy nor RT differed across prior time levels. We consider several possible explanations for this null finding. The most parsimonious account is a ceiling effect: because supraliminal cues provided explicit, consciously available temporal information, participants could prepare equally well across all prior time levels, resulting in uniformly high performance that obscured condition-specific differences. This interpretation is consistent with established findings that explicit temporal cues reduce temporal uncertainty and support optimal motor preparation regardless of specific interval durations (e.g., Coull & Nobre, 1998; Los & Heslenfeld, 2005). A second possibility is that the absence of effects reflects insufficient statistical sensitivity rather than a true null effect. Supraliminal temporal cueing paradigms often yield smaller effect sizes than subliminal variants, and our sample may have been underpowered to detect subtle differences between peak conditions.

Another observation in Experiment 2 was that temporal expectations formed by participants based on supraliminal cues could transfer to subliminal cues, consistent with Faivre et al''s (2014) findings in multisensory information integration (Faivre et al., 2014). This result reveals the possible role of supraliminal experience in subliminal perception—that supraliminal experience can facilitate participants' utilization of information contained in subliminal cues.

Furthermore, the contrasting outcomes between Experiments 1 and 2 themselves provide indirect evidence for the validity of the subliminal manipulation. Had the 15-ms masked cues been consciously perceived, participants in Experiment 1 should have been able to form temporal expectations on the basis of those cues, just as participants in Experiment 2 did during the supraliminal learning phase. The fact that temporal expectations were absent in Experiment 1 but emerged in Experiment 2 following supraliminal experience suggests that the two types of cues engage qualitatively different cognitive processes. This dissociation is consistent with the interpretation that the brief masked cues in Experiment 1 remained below the threshold of conscious awareness. The forced-choice awareness test (Experiment 4) further corroborated this interpretation, confirming that participants were unable to discriminate cue shapes above chance level.

Across all three experiments, participants showed decreasing RTs and decreasing accuracy as the experiments progressed. The decrease in accuracy was unexpected, but may be a speed-accuracy trade-off resulting from decreased RTs. Many studies have shown that when participants respond faster, accuracy decreases, whereas improved accuracy is accompanied by increased RT (Reuss et al., 2015). To examine whether a speed-accuracy trade-off existed in our results, for each participant's data in Experiments 1 and 2, we conducted a binary logistic regression with judgment accuracy as the dependent variable and RT, cued prior time duration, actual prior time duration, match between cued and actual prior time duration, and whether actual prior time duration was a peak as independent variables. We then performed one-sample t-tests on the beta coefficients for RT across all participants in that experimental condition. Results showed that in both Experiments 1 and 2, the beta coefficients for RT were significant (Experiment 1: beta =

-.004, $t(15) = -3.769$, $p = .002$, *Cohen's* $d = 0.942$; Experiment 2: beta = -.005, $t(15) = -6.018$, $p <$ .001, *Cohen's* $d = 1.505$). For Experiment 3, for each participant's data, we conducted a binary logistic regression with judgment accuracy as the dependent variable and RT, actual prior time duration, and whether actual prior time duration was a peak as independent variables. Similarly, we performed one-sample *t*-tests on the resulting beta coefficients for RT. Results again showed that the beta coefficient for RT was significantly less than zero (beta = -.005, $t(16) = -4.753$, $p < .001$, *Cohen's* $d = 1.153$). Participants' RT was negatively correlated with accuracy; that is, the lower the accuracy, the faster the response, and when accuracy was higher, responses were relatively slower. Therefore, as the experiments progressed, the decrease in accuracy and reduction in RT were likely the result of a speed-accuracy trade-off. It should be noted that in Experiment 2, RTs did not differ significantly between the short peak condition (594 ms) and the long peak condition (587 ms); therefore, the significant difference in accuracy (short peak: 0.818; long peak: 0.766) cannot be explained by RT differences. We believe that the dissociation in accuracy between short and long peak conditions observed under the subliminal old cue condition in Experiment 2 was caused by participants forming temporal expectations based on the subliminal sensory consequences of actions.

However, several limitations and alternative explanations should be considered when interpreting the present findings. The asymmetric effect—where temporal expectations only emerged in the short peak condition under subliminal cueing—is consistent with previous results (Correa et al., 2004; Thomaschke et al., 2011b), as the rising hazard function in the long peak condition allows participants to dynamically reorient attention, thereby washing out initial cueing effects. However, the absence of broader temporal orienting effects may also reflect insufficient trial counts for stabilizing complex cue-time mappings (Thomaschke & Dreisbach, 2013), substantial individual variability in masking thresholds and suppression depth (Kouider & Dehaene, 2007), and task difficulty or ceiling effects once participants learned to prepare optimally for both peak conditions.

It is also important to note that the experimental order was fixed across both experiments (supraliminal → subliminal old-matched → subliminal new-matched). This fixed sequence introduces a potential confound between order/practice effects and condition effects, meaning that observed differences across conditions could partly reflect accumulated practice or fatigue rather than the experimental manipulations per se. Although we partially addressed this for RTs in Experiment 2, we acknowledge that this remains a substantial limitation of the current design. Future studies should ideally counterbalance the order of conditions or employ a randomized presentation to rule out order-related confounds.

Conclusion

Our findings demonstrate that when the sensory consequences of an action are consciously perceived, participants are able to form temporal expectations for subsequent events based on those consequences. These established temporal expectations can then transfer to the subliminal (subthreshold) sensory consequences of an action. In the absence of prior experience forming expectations based on supraliminal (above-threshold) consequences, we did not detect the formation of temporal expectations based on subliminal consequences alone. This suggests that supraliminal experience plays, at the very least, a facilitatory role in the development of temporal expectations based on subliminal sensory outcomes.

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Lihan Chen: Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing – original draft; Writing – review & editing.

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