Spatial distance and temporal attentional focus modulate voluntary action preparation and awareness

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Abstract

Peripersonal space (PPS)—the immediate space surrounding the body—modulates perception and motor control. However, its impact on how voluntary actions are initiated and subjectively experienced remains underexplored. Similarly, how directing attention to different phases of an action, such as intention formation versus execution, and anticipating outcomes of an action, modulates the neural readiness for movement, has yet to be fully examined. This study investigates whether spatial proximity, attentional focus, and anticipated action outcomes influence action preparation and action awareness, using a virtual reality adaptation of the Libet clock paradigm during EEG recordings. Neural results reveal that attentional focus and anticipated action outcomes modulate different phases of motor preparation, as indexed by the readiness potential (RP)—a gradual buildup of neural activity preceding voluntary movement. Focusing on decision timing (without subsequent action outcomes) enhances early RP amplitude and decreases the late RP slope, suggesting increased preparatory neural engagement during intention formation. In contrast, focusing on action execution leads to a steeper late RP slope, indicating later and faster motor activity buildup when attention is directed toward movement onset. Anticipating action outcomes increased late RP slope, which was accompanied by the temporal binding effect: when a tone followed the action, both decision and action estimates shifted toward it. Spatial proximity influences RP dynamics specifically in tasks when participants focused on their intention to act in the absence of an outcome. Behavioural results show that actions are perceived as occurring earlier when the clock is displayed near compared to far, indicating that PPS influences the temporal perception of action timing. Overall, these findings highlight the dynamic interplay among external spatial context and internal cognitive processes in shaping motor preparation and action awareness. Importantly, a temporal internal attentional focus on intention to act modulates early RP—traditionally considered an unconscious stage of neural readiness. These results contribute to a deeper understanding of how PPS and the locus of attention on specific action phases affect action preparation and awareness, with potential implications for future research on the sense of agency and voluntary action decision making.

Keywords

Readiness potential, voluntary action, motor preparation, action awareness, spatial proximity, attentional focus, action outcome, temporal binding

Introduction

Voluntary actions are often referred to as self-initiated actions that are produced without any immediate external incentives, such as rewards or impending threats, and are instead initiated endogenously (Haggard, 2008, 2017; Passingham et al., 2010). This self-generation aspect is a critical facet of conscious control and the initiation of our actions. Notably, it has been consistently shown that these self-initiated actions are preceded by the Bereitschafts-potential (BP), also known as the "readiness potential" (RP), which is a slow build-up of negative EEG potential originating from pre-motor cortical areas (Kornhuber & Deecke, 1965), starting up to two seconds prior to self-initiated movements (Kornhuber & Deecke, 1965; Shibasaki & Hallett, 2006). The RP was first reported by Kornhuber & Deecke (1965) and later gained great attention through Libet et al.'s famous study, which claimed that the onset of the RP occurred several hundred milliseconds prior to the decision to move (Libet et al., 1993; Libet et al., 1983). The timing of this decision was obtained by asking participants to report the time on a rotating clock when they first became aware of their intention to move (referred to as the will-time or W-time). Libet's study suggested that the RP precedes conscious awareness of movement intention, igniting debates about its role in volitional control (Schmidt et al., 2016; Schurger et al., 2021; Triggiani et al., 2023).

The RP is commonly characterized as having an early and a late component based on the scalp distribution and the gradient of their negative potentials (Oken & Phillips, 2009; Shibasaki & Hallett, 2006). The early component (early RP, ~2000 ms to ~500 ms prior to movement onset) is slow and prolonged, with a gradual increase in negativity, which is localized symmetrically in the bilateral supplementary motor area (SMA) and premotor cortex, and was thought to represent the more general preparation for the forthcoming movement. In contrast, the late component (late RP) has a much steeper slope generated by activity in the contralateral primary motor cortex (M1), starting around ~500 ms prior to movement onset (Shibasaki & Hallett, 2006).

Numerous studies have shown that the amplitude of the RP is influenced by various factors, which differ according to experimental paradigms. For instance, RP amplitude increases when participants consciously perceive themselves as preparing to move. This has been shown when participants made self-paced movements and reported their intention status in response to random visual probes (Parés-Pujolràs et al., 2019; Schultze-Kraft et al., 2020). However, recent findings employing alternative probing methodologies suggest that the RP might not reliably reflect the emergence of conscious intention, highlighting ongoing debates about its precise relationship to conscious volition (Gavenas et al., 2025). Additionally, RP amplitude is greater in self-initiated actions compared to externally cued movements (Takashima et al., 2018) and in freely chosen actions compared to externally guided selections (Takashima et al., 2020).

Further, prior work has shown that when participants attempted to replicate the interval between two tones using two consecutive button presses, the early component of the RP (1600-800 ms before movement onset) was significantly larger preceding the second action which required attention to movement timing—unlike the first action, whose timing was incidental (Baker et al., 2012). Recent neurophysiological studies showed that the neural mechanisms underlying the RP are

integrated with action timing processes, suggesting a critical role for RP in the temporal organization of voluntary actions (Emmons et al., 2017; Fifel, 2018). Moreover, predictive sensory outcomes of intended actions have been shown to amplify RP magnitude, supporting the view that RP reflects the integration of motor preparation and sensory prediction (Reznik et al., 2018; Vercillo et al., 2018; Wen et al., 2018). Beyond motor preparation, RP has been identified to encompass decision-related, non-motoric cognitive processes, further complicating interpretations of its functional role (Alexander et al., 2016; Schmidt et al., 2016). Thus, findings about how conscious intention, attentional allocation, and sensory outcome prediction influence the RP across studies employing different paradigms remain heterogeneous and sometimes conflicting (Gavenas et al., 2025; Triggiani et al., 2023). Moreover, previous studies have typically examined attentional focus using isolated manipulations of timing or outcome prediction, often in contexts where action reports were not required. In contrast, the present study introduces an integrative approach by examining how attentional focus (toward decision vs. action), and anticipated action outcomes interact to shape both RP dynamics and subjective action awareness.

Despite this extensive research on the modulation of the RP, one important dimension that has not been explored is the external spatial distance of the visual objects with which we interact. Spatial proximity, termed here as peripersonal space (PPS), i.e., the space immediately surrounding our body, is known to influence decision-making processes, urgency to act and the awareness of the voluntary action (Blini et al., 2018; Brozzoli et al., 2012; Brozzoli et al., 2011; Dureux et al., 2021; Kong et al., 2024; O'Connor et al., 2021; Patané et al., 2020). Despite its relevance to action execution, the role of PPS in voluntary action preparation and awareness remains underexplored. A recent study showed that objects' proximity, namely positioning a Libet's clock (Libet et al., 1983) within the PPS, led to earlier movement initiation, suggesting increased motor urgency. This proximity also affected the subjective awareness of both the decision to act and, to a larger extent, the execution of the action (Kong et al., 2024). These behavioral findings highlight the need to investigate whether such spatial proximity effects extend to the neural level—specifically, whether they modulate the RP.

The present study addresses this gap by examining how spatial proximity, in addition to attentional focus and anticipated action outcomes, influences RP dynamics and action awareness. In this context, we employ a modified Libet clock within a virtual reality setup to evaluate the RP as participants interact with visual stimuli (the clock) located within or outside their PPS. Importantly, our paradigm allowed for the simultaneous manipulation of this spatial factor and the temporal attentional focus within the same voluntary action task—a design not previously explored in RP research.

We hypothesize that directing attention towards the reporting of the decision or the execution of an action, will modulate the RP. Specifically, we anticipate that decision-focused attention will enhance the early phases of the RP, while action-focused attention will augment the later phases. Anticipated outcomes are also expected to influence the RP, reflecting the brain's predictive mechanisms (Polezzi et al., 2008; Reznik et al., 2018). Additionally, spatial distance, as suggested by our preceding work (Kong et al., 2024), may also modulate the RP, with objects closer to the body potentially eliciting stronger responses. This investigation seeks to provide new insights into the

features that shape the RP during voluntary actions, enhancing our understanding of the relationship between spatial factors, internal cognitive processes and neural activity.

Methods

Participants

Twenty-four healthy participants (14 females, age = 25.3 ± 3.9 years) were recruited for this study. All participants were right-handed and unaware of the study's aims and reported normal or corrected-to-normal vision, normal hearing, and no history of neurological disorders. Informed consent was obtained from each participant before their involvement in the study. They received a compensation of €30 for their participation. The study procedures were approved by the ethics committee (CEEI/IRB Comité d'Evaluation Ethique de l'Inserm, n°21-772, IRB00003888, IORG0003254, FWA00005831). The study adhered to the ethical standards of the Declaration of Helsinki.

Material and apparatus

We adapted the Libet clock paradigm (Haggard et al., 2002; Libet et al., 1983) to a VR setup (Kong et al., 2017; Kong et al., 2024) to obtain stereoscopic vision of the clock. Participants sat comfortably and wore a head-mounted display (HMD, Oculus Rift CV1, resolution 2160 × 1200) while performing the task **(Fig. 1A)**. The virtual environment included a virtual room with two long, high, squared walls spaced 1.84 m apart, providing depth perception, and a virtual clock face **(Fig. 1B)** that participants were asked to fixate on. The clock face was marked with conventional "5-min" intervals, and had a 'hand' in the form of a green dot, which rotated clockwise with a period of 2560 ms per circle. The clock was presented randomly either at a distance close to (45 cm) or far from participants (3 m). The diameter of the near clock was 0.24 m, and the diameter of the far clock was 1.8 m, with both clocks having a visual angle of 29.86 degrees. Thus, the retinal size of the clock in the near and far space was corrected to avoid any potential size-dependent confound, as done in previous studies (Kong et al., 2024; Blini et al., 2018; Dureux et al., 2021; O'Connor et al., 2021). Before beginning formal testing, participants were asked to estimate the distance of the near and far clocks from themselves. The average estimations confirmed that perceived distances aligned with our intended presentation: near (Mean = 0.39 m, SD = 0.26 m) and far (Mean = 2.26 m, SD = 0.93 m).

The key press was performed on a computer keyboard with the participants' right index finger at a time of their own choice. The action consequence, when there was one, was an auditory tone (44.1 kHz, 30ms duration, starting 250 ms after the keypress) played over the built-in headphone of the Oculus. During the inter-trial interval, a fixation square was displayed at the centre of the upcoming virtual clock and at the middle distance between the near and far space. The visualizations were programmed using the Unity platform (Unity 2018.4.22f1 Personal) and Microsoft Visual Studio 2019.

EEG and EMG recording

EEG data were continuously recorded from nine scalp sites (T7, C5, C3, C1, Cz, C2, C4, C6, and T8) using active electrodes (ActiCap, Brain Products) attached to an EEG cap (EASYCAP GmbH), positioned according to the extended international 10/20 system **(Fig. 1C)**. The signal was recorded

with a sampling frequency of 2500 Hz using Vision Recorder (Vision Recorder. Ink). The ground electrode was placed on Fpz, and all electrodes were online referenced to the right ear lobe. For stimulus presentation and behavioural response recording, Unity software was employed on the experimental control computer, which was synchronized with the EEG recording system. Event information for each trial was transmitted to the EEG system using a parallel port, ensuring accurate alignment of behavioural and EEG data. Electromyogram (EMG) signals were bipolarly recorded from the extensor digitorum muscle in the forearm via surface electrodes (Ambu® Neuroline 700), facilitating the precise temporal detection of the finger's movement onset.

Stimulus and experimental design

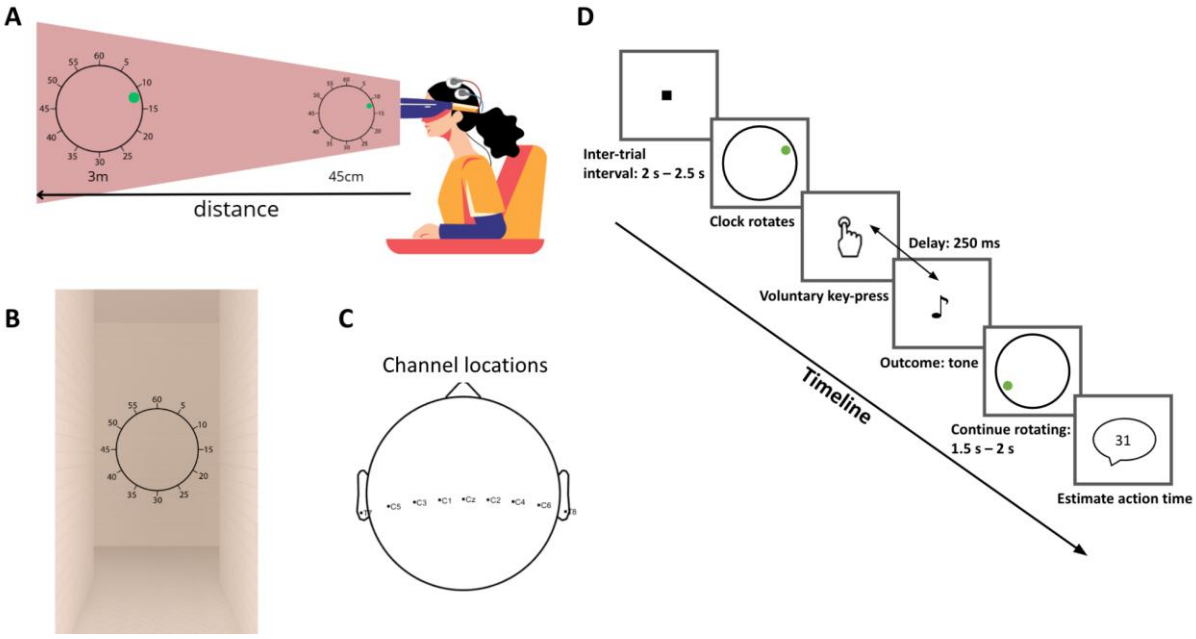

Figure 1. Experimental setup and schematic illustration of the task. (A) Illustration of the experimental setup: participants wore a VR headset for immersive display of the visual stimuli (rotating clocks) presented either in near space (45 cm) or far space (3 m). Clocks were rendered with size scaling to ensure identical retinal size across distances. Participants also wore an EEG cap with active electrodes, and surface EMG was recorded from the right extensor digitorum muscle to allow offline detection of movement onset. (B) Example of the virtual environment from the participant's perspective, depicting a rotating clock embedded in a 3D-rendered corridor scene. (C) Top view of the EEG electrode configuration showing the nine central channels: T7, C5, C3, C1, Cz, C2, C4, C6, and T8. (D) Schematic representation of the trial structure in the Action Operant task. Each trial began with a fixation cross (2–2.5 s), followed by the appearance of a rotating clock. Participants made a voluntary keypress, which was followed by a 250 ms delay and an auditory tone (outcome). The clock continued rotating for another 1.5–2 s, after which participants verbally reported the position of the clock hand at the moment they believed they acted.

Table 1. Overview of the experimental tasks

Task Name	Voluntary Action (Key-press)	Action Outcome (Tone presence)	Attentional Focus (Report instruction)	Clock Distance
Tone-only	✗	✔	Tone	Near / Far

Action-only	✔	✗	None	Near / Far
Decision Baseline	✔	✗	Decision	Near / Far
Decision Operant	✔	✔	Decision	Near / Far
Action Baseline	✔	✗	Action	Near / Far
Action Operant	✔	✔	Action	Near / Far

✔ = Yes; ✗ = No. 'Near' and 'Far' refer to the spatial position of the clock relative to the participant (within or outside peripersonal space). This table summarizes the six tasks used in the study. All tasks involved voluntary key-presses except Tone-only, and varied in terms of action outcome, report instruction, and spatial proximity.

Our experiment consisted of a series of separate tasks unified by a commonly adapted Libet's clock paradigm (Table 1). At the core of this paradigm was the observation of a rotating clock hand (**Fig. 1B**), with participants engaging in various tasks that involved key presses and/or auditory tone **(Fig. 1D)**. The primary difference between tasks lay in the specific event that participants were required (or not) to report. Each participant took part in all tasks, following a within-subject design.

Tone-only task: Here, participants did not perform any key press. Instead, they were asked to report the timing of a tone that was randomly played by the computer, occurring 3 to 4.5 seconds after the onset of each trial (e.g., the onset of clock rotation). The experimenter then input their reports with another computer keyboard and did so for all other tasks that required participants' reports (i.e., all tasks except the Action-only task). This single-event task provides a context to contrast against the other single-event task below (Action-only task) that only involves active movements.

Action-only task: After the clock hand started rotating, they could press the 'zero' key on a computer keyboard using their right hand index finger when they felt the urge to do so; in other words, at a time of their own choice. At odds with previous studies, to assess potential variations in the natural buildup of urgency, participants here were not instructed to wait until the clock rotation had completed at least one cycle. This set the baseline for natural action initiation. Once they pressed the key, the clock kept on rotating for a random duration (1.5 to 2s) before disappearing. The instructions for pressing the key and the rotation of the clock were the same for all tasks with a key press (i.e., all tasks except Tone-only task, see above).

Decision baseline task: building upon the Action-only task, participants were additionally asked to verbally report at the end of the trial where the rotating hand was when they first became aware of their decision to press the button — referred to as "W-time" in Libet experiments (Libet et al. 1983). **Decision operant task**: similar to the Decision baseline, but here, a tone followed the key press after a 250 ms delay, allowing us to study the effect of predictable auditory consequences on decision reporting.

Action baseline task: participants estimated the timing of their key press, focusing on action timing. **Action operant task**: mirroring the Action baseline, but including a 250 ms delayed tone post-

key press, to explore the influence of predictable auditory consequences on the reporting of action execution **(Fig. 1D)**.

These tasks collectively allowed us to investigate the influences of peripersonal space, temporal attentional focus, and action outcomes on the RP. For all tasks, a fixation square was presented during the inter-trial interval with a random duration between 2s and 2.5s, followed by the appearance of the virtual clock and the initiation of the clock's rotation **(Fig. 1D)**. Compared to our recent study (Kong et al., 2024), this longer inter-trial interval was chosen in order to obtain a stable and noise-free baseline for EEG signals. For each task, 50 trials were performed for the near and far spaces, respectively, in a random order, in line with previous studies showing that the RP is best identified through averaging a large number (>30) of trials (Schurger et al., 2021). Notably, the distance at which the clock was displayed (45 cm or 3 m) was task-irrelevant **(Fig. 1A)**. Participants underwent 2 trials for familiarization before the formal testing in each task. The Tone-only was always the initial task, with all other tasks presented in a counterbalanced order.

Data analysis

EMG analysis: Semi-automatic detection of movement onsets

For each trial, a high-pass Butterworth filter with a 10 Hz cutoff was applied to the EMG signals. EMG onset was then semi-automatically detected as follows (See also **Supp. Fig. S1** for the illustration of the EMG onset detection method). The signal was first transformed into its envelope. Then, the Peak was detected as the local maxima within the [350-0 ms] window preceding the computer-registered keypress. The baseline was calculated as the average signal over the period from 100 ms to 200 ms after the trial onset. The onset of the movement was defined as the time, within the [-350 0 ms] before the keypress, when the EMG envelope signal exceeded 50% of the Peak-Baseline difference. To augment the precision of our method, we integrated an interactive graphical user interface (GUI). This GUI enables manual marking of EMG activity onset, providing the flexibility for the onset to be identified even outside the predefined time window. This blend of automated processing and manual input allows for a more accurate determination of muscle activity onset.

EEG analysis: Readiness potential (RP)

EEG data were preprocessed and analysed using custom Python scripts and the MNE package for Python (Gramfort et al., 2013). Each task of each participant was preprocessed separately as follows: continuous EEG was filtered with a 0.1 Hz high-pass filter, a notch filter at 50 Hz, and a 30 Hz low-pass filter, followed by artifact correction using the *Autoreject* algorithm. EEG data from the Cz channel were epoched between -1.2 and 0.1 s around either the computer-recorded keypress, or the EMG movement onset. For the Tone-only task, EEG data from the Cz channel were epoched between -1.2 and 0.1 s around the tone onset. Additionally, epochs containing large artifacts (± 100 μV) were excluded from the analysis.

Given that we do not know when volition begins, we cannot determine the appropriate baseline for analyzing the RP (Haggard, 2024). Additionally, in light of the concerns that baseline

correction may artificially influence RP amplitude differences—potentially leading to misleading results (Delorme, 2023; van Driel et al., 2021), we opted to analyze and report our data without applying baseline correction. The early RP was quantified as the average amplitude during the first 600 ms [-1200 to -600 ms], while the late RP was the average amplitude of the following 600 ms [-600 to 0 ms]. In addition to analysing the early and late components of the RP, we also focused on the slope of the late RP, as slopes are less affected by baseline correction issues. The slope of the late RP was calculated by subtracting the average of 50 ms preceding the late RP component [-650 to -600 ms] from the average of the last 50 ms [-50 to 0 ms]. This difference was then normalized by the 600 ms duration, representing the rate of change in the late RP signal (Jo et al., 2014).

A three-way repeated measure ANOVA with balanced factors 2 (distances: near vs. far) × 2 (report instructions: decision vs. action) × 2 (tone presence: baseline vs. operant) was conducted separately for the early RP, late RP and late RP slope. Additionally, a two-way repeated measures ANOVA with factors 2 (distances: near vs. far) × 2 (Task: action vs. tone) was performed for Tone-only and Action-only tasks. One sample t-tests were also conducted for the Tone-only and Action-only tasks, respectively, to further assess whether the typical RP profile appears only in the action task rather than in response to an external stimulus.

Subjective awareness analysis

To investigate the impact of distance on the subjective awareness of action decision, execution, and the existence of temporal binding induced by the presence of a tone, we considered all tasks with a report (i.e., all tasks except the Action-only task) and we calculated time estimates as follows. First, we converted the reported position of the clock in milliseconds. Then, for the action report and tone report tasks, the actual time of the keypress (or the tone, respectively) was subtracted from the subjective reported time of the action (or the tone, respectively). These estimated times thus correspond to action and tone judgment errors. The values were negative when the event (action or sound) was subjectively perceived before the actual event. Similarly, for the decision report tasks, the time of the keypress was subtracted from the subjective reported time of the decision. The values were negative when the decision was subjectively perceived before the actual action. A 2 × 2 × 2 repeated measure ANOVA was performed on the estimated time with the factors clock distance (near, far), report instruction (decision, action), and tone presence (baseline, operant). Additionally, a paired t-test was carried out for the Tone-only task.

Movement time (MT) analysis

To explore how proximity influences action initiation time, we calculated the mean movement time across trials for each task that involved a keypress (i.e., all tasks except the Tone-only task). This calculation entailed determining the time elapsed between the onset of the clock rotation and the computer-registered keypress (keypress movement time or keypress MT), or the initiation of movement as detected in the EMG recordings (EMG MT). A paired t-test was conducted for the Action-only task to provide insights into the effects of the distance of the clock from the body on action initiation when participants had nothing to report. In addition, a three-way rmANOVA 2 (distances: near vs. far) × 2 (report instructions: decision vs. action) × 2 (tone presence: baseline vs. operant) was

run on all other tasks. Both the paired t-test and the ANOVA were run separately on keypress MT and EMG MT.

None of the factors significantly influenced either the computer-registered keypress time or the EMG-detected movement onset time, see details in supplemental material **(Supp. Fig. S2)**. However, the observation of the distribution of the difference of MTs between keypress and EMG showed that most of the MT difference falls within the critical range of 0 to 0.1 seconds, but an interesting second part of the distribution occurred within 0.1-0.5s. To further characterize the dynamics of movement initiation, we quantified the differences between keypress MT and EMG MT and we calculated for each participant the proportion of these differences that fell within the second part (exceeding 0.1 and below 0.5 seconds - note that the difference exceeded 0.5 s in a minimal number of trials - means for each task ranged between 0.1% and 1.4%) (see **Supp. Fig. S3**). These percentages were then subjected to the same three-way repeated measures ANOVA. Note that the data of these percentages in the Action baseline and Action operant tasks were found to be non-normally distributed. We nevertheless proceeded with the ANOVA analysis as our experiment was explicitly designed as a factorial experiment and designed to test whether there were interactions: balanced ANOVA is quite robust to departures from normality (Montgomery, 2017). Post-hoc two-by-two comparisons were tested with both Wilcoxon signed-rank tests and t-tests for tasks in which there were normality violations. As the pattern of statistical significance was unchanged with both types of tests, only the latter is reported in this manuscript.

All the data analyses were carried out using customized MATLAB programs (2019b, Mathworks, Natick, MA) and Python 3.0. All statistical analyses were performed using the IBM SPSS statistical package (SPSS 29.0). The significance level was set at $\alpha = 0.05$, and Bonferroni correction was applied for multiple comparisons.

Results

EEG results

To characterize the influence of clock distance, report instruction and tone presence on the shape of the RP in both epochs aligned on computer-recorded keypress **(Fig. 2)** and epochs aligned on EMG movement onset **(Supp. Fig. S4)**, we calculated the slope of the late RP, early RP average, and late RP average. The analyses on both types of epochs yielded consistent results. Therefore, for conciseness, only the detailed findings on the epochs aligned on computer-recorded keypress are reported **(Fig. 3)**. It should be noted that 'larger' metrics indicate greater negative values.

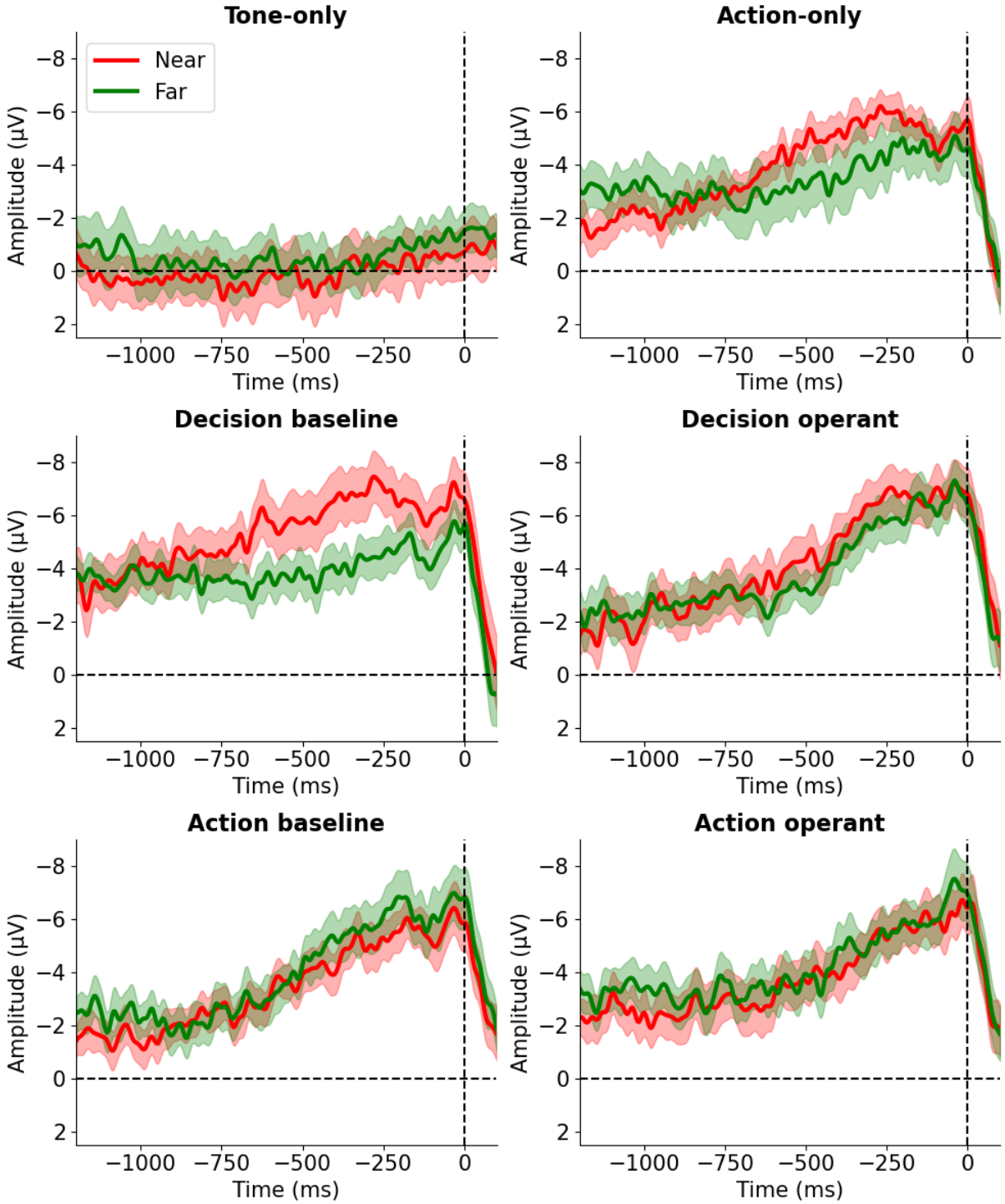

Figure 2. The time-course of readiness potential (RP) without baseline correction across different experimental tasks (described in Table. 1). The vertical dashed line at time zero represents the computer-recorded keypress for the first five tasks or the tone onset for the "Tone-only" task. Red: clock presented near; Green: clock presented far. The shaded regions surrounding each line represent one standard error of the mean.

The two-way repeated measures ANOVAs were conducted on the early RP average, late RP average and late RP slope for the Tone-only and Action-only tasks. A significant main effect of Task was found for both the early RP ($F(1,24) = 4.68$, $p = .04$, partial $\eta^2 = .16$) and on the late RP ($F(1,24) = 19.90$, $p < .001$, partial $\eta^2 = .45$), with greater early and late RP amplitudes in the Action-only compared to the

Tone-only task. No other main effects or interactions were found ($p > .21$). To further investigate the presence of the RP, one-sample t-tests were conducted against zero. In the Tone-only task, none of the RP components (late RP slope, late RP average, early RP average) differed significantly from zero (all $p > .37$), indicating the absence of a typical RP profile in the absence of movement. In contrast, all three RP measures in the Action-only task were significantly different from zero (early RP average: near $p < .001$, far $p = .004$; late RP average: near and far $p < .001$; late RP slope: near $p = .026$, far $p = .022$), reflecting a robust RP signal. These findings confirm that a reliable RP profile emerges only in the presence of voluntary movement, and is absent when no action is performed.

The three-way repeated measure ANOVA was conducted for the balanced tasks involving keypress and reports, with the factors clock distance (near, far), report instruction (decision, action), and tone presence (baseline, operant). For the early RP average (**Fig. 3A**), the interaction between the report instruction and tone presence was significant ($F(1,24) = 8.61$, $p = .007$, partial $\eta^2 = .26$). Pairwise comparisons revealed that the early RP average was significantly larger in the decision baseline task than in the decision operant task (Mean difference ± SE = -1.38 ± 0.67, $p < .05$, 95% CI [-2.76, -0.004]), and than in the action baseline task (Mean difference ± SE = -1.74 ± 0.49, $p = 0.002$, 95% CI [-2.74, -0.74]). These results indicate that the early RP amplitude was enhanced in decision baseline task, possibly suggesting stronger neural engagement in early preparatory activity when participants attend to their decision without the expectation of an external outcome. No other significant main effects or interactions were found ($p > .16$).

For the late RP average (**Fig. 3B**), the interaction between the report instruction and clock distance was significant ($F(1,24) = 7.70$, $p = .01$, partial $\eta^2 = .24$). Pairwise comparisons revealed that in the decision reporting tasks, the late RP average was significantly larger when the clock appeared in near space compared to far space (Mean difference ± SE = -1.36 ± 0.55, $p = .02$, 95% CI [-2.49, -0.23]). No significant main effect or interaction was found ($p > .23$). These results indicate that the modulation of the late RP amplitude by spatial proximity is specific to decision-reported tasks.

For the late RP slope (**Fig. 3C**), it revealed a significant main effects of tone presence ($F(1,24) = 12.07$, $p = .002$, partial $\eta^2 = .34$), and a significant interaction between report instruction and tone presence ($F(1,24) = 6.25$, $p = .02$, partial $\eta^2 = .21$). Pairwise comparisons revealed that the late RP slope was significantly shallower in the decision baseline condition than in the decision operant condition (4.29 ± 1.19, $p = .001$, 95% CI [1.84, 6.74]), and than in the action baseline condition (3.78 ± 1.20, $p = .004$, 95% CI [1.32, 6.25]), and than in the action operant condition (3.88 ± 1.20, $p = 0.004$, 95% CI [1.40, 6.35]). The main effect of report instruction was not significant ($F(1,24) = 2.97$, $p = .098$, partial $\eta^2 = .11$). No other significant main effects or interactions were found ($p > .13$). These results suggest that the late RP slope becomes steeper in tone-present conditions, indicating a more rapid buildup of neural activity prior to movement execution. Additionally, the shallowest late RP slope was found in decision baseline task, which aligns with the results reported for the early RP average.

Note that no significant correlation was found between movement time and these RP metrics, including the early RP average (adjusted $p > 0.24$), late RP average (adjusted $p > 0.4$) and late RP slope

(adjusted p > 0.1), ruling out movement time (and other associated factor such as time monitoring) as a potential contributing factor to the effects observed in our study.

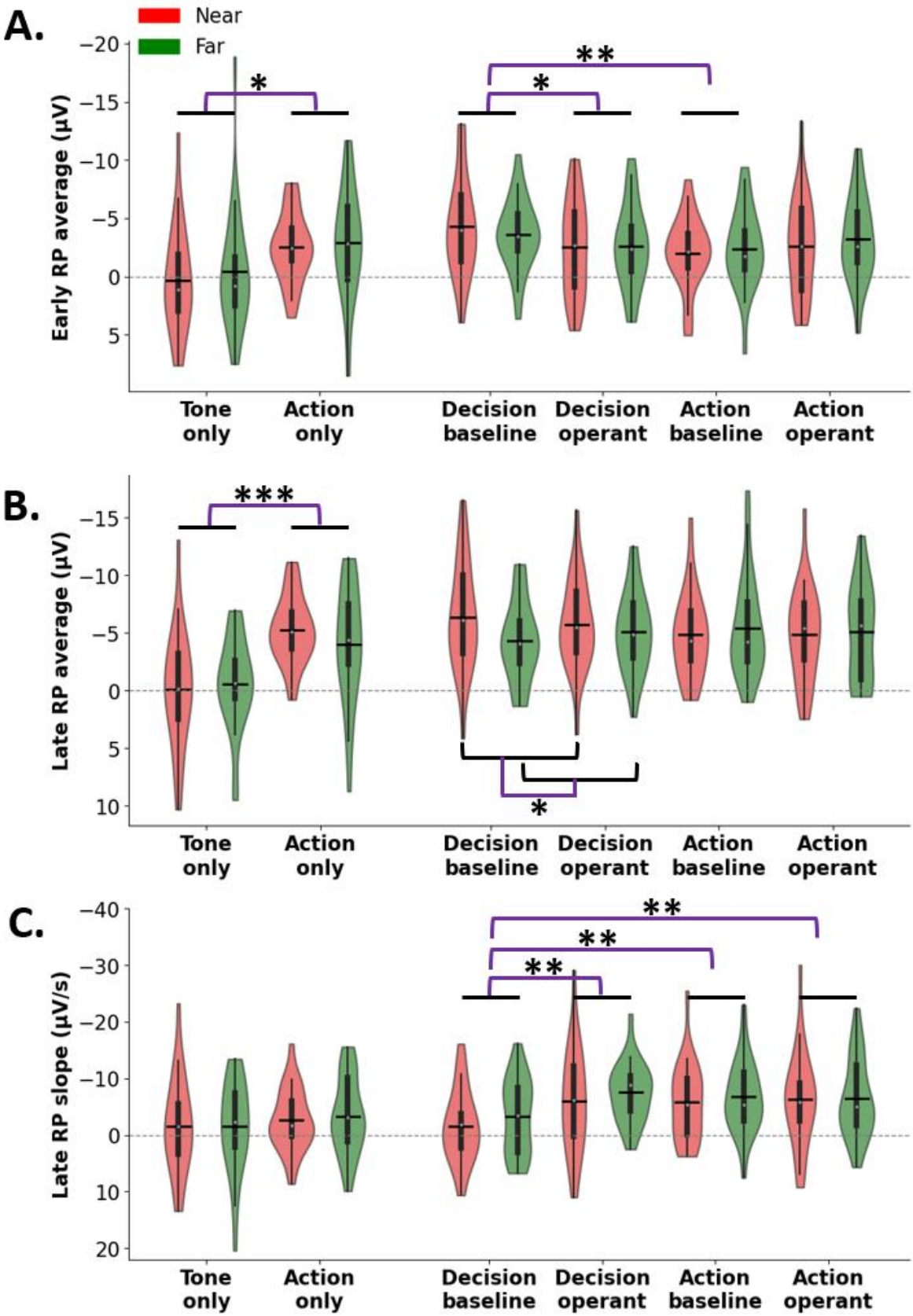

Figure 3. RP metrics for each experimental task (without baseline correction). A. Early RP averages; **B.** Late RP averages; **C.** Late RP slopes. Note that greater negative potentials represent a greater amplitude from 0 and that negative slopes indicate a steeper negative descent in potential. The 'Near' condition is represented by red violins, while the 'Far' condition is depicted by green violins. The width of each violin represents the probability density of data points at different RP metrics. The white dot within each violin represents the median RP metrics, the thick vertical line represents the interquartile range, and the horizontal black bar represents the mean RP metrics within each task. ** for $p < 0.01$, * for $p < 0.5$.

Subjective awareness of action decision and action execution

Except in the Action-only task, participants were required to report the estimated time of their decision, their action or just a tone played by the computer **(Fig. 4)**. The paired t-test for the Tone-only task showed no significant difference between the tasks in which the clock was near (Mean ± SE = 134.75 ± 8.84) and far (Mean ± SE = 133.50 ± 7.88 s, $t(24) = 0.38$, $p = .71$). This suggests that the distance of the clock from the body did not affect time perception itself when there was no voluntary movement involved.

The 2 × 2 × 2 repeated measure ANOVA on the estimated time of tasks involving a keypress and a report, with the factors of distance (near, far), report instruction (decision, action), and tone presence (baseline, operant), did not show a significant main effect of distance ($F(1,24) = 3.18$, $p = .087$, partial $\eta 2 = .12$). The main effect of report instruction was significant ($F(1,24) = 96.51$, $p < .001$, partial $\eta 2 = .80$): as expected, participants perceived their decision as occurring earlier than their action. In particular, the interaction between distance and report instruction was not significant ($F(1,24) = 0.66$, $p = .42$, partial $\eta 2 = .03$). Nonetheless, aligning with our *a priori* hypothesis, based on our recent study (Kong et al., 2024), that a distance effect could be present for action estimates more than for decision estimates, an ANOVA was separately performed for decision and action estimates and showed a significant main effect of distance in the action estimates tasks ($F(1,24) = 6.18$, $p = .02$, partial $\eta 2 = .21$) but not in the decision estimates tasks ($F(1,24) = 0.10$, $p = .75$, partial $\eta 2 = .004$), suggesting that the action time was reported significantly earlier in the near relative to the far space.

Additionally, the ANOVA showed that the main effect of tone presence was highly significant ($F(1,24) = 20.48$, $p < .001$, partial $\eta 2 = .46$). This indicated that both the perceived times of decision and action were shifted towards the tone compared to when there was no tone. Thus, there was a temporal binding between the perceived time of action and its consequence, as well as between the perceived time of decision and the subsequent consequence. No other interactions were significant ($p > .26$).

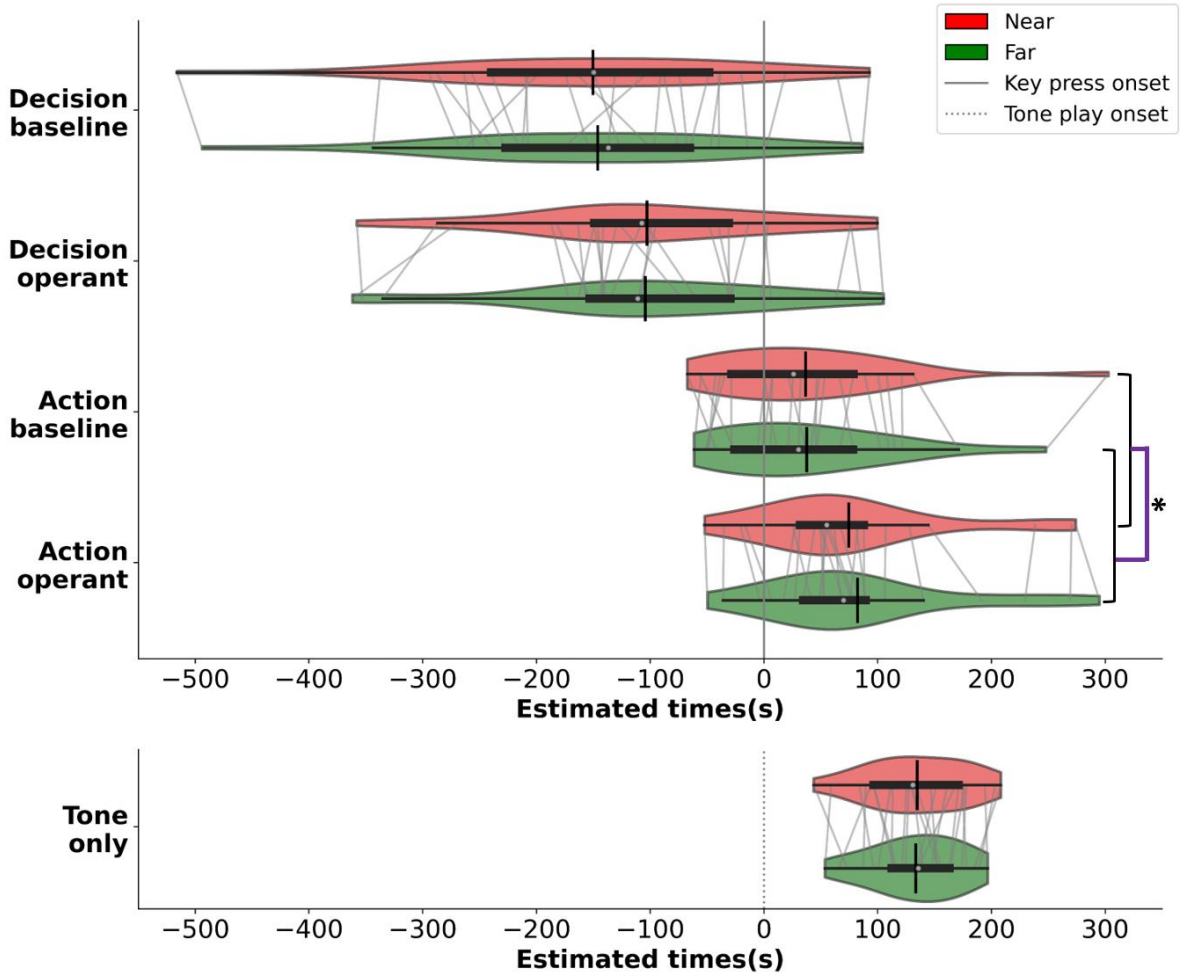

Figure 4. The distribution of estimated times for Decision estimates, Action estimates and Tone-only estimates. The red and green violins distinguish between near and far distances, respectively. For the subplots of "Decision estimates" and "Action estimates", the x-axis is centred around the key-press onset (a solid vertical line), showcasing estimated time variations in relation to key-press time. For "Tone-only estimates", the x-axis is centred around the tone play onset (a dotted vertical line). The width of each violin represents the probability density of data points at different times. The white dot within each violin represents the median estimated times, the thick horizontal line represents the interquartile range, and the vertical black bar represents the mean estimated times within each task.

Movement times based on computer-registered keypress and EMG movement onset

As mentioned in the data analysis section, neither the computer-registered keypress time nor the EMG-detected movement onset time was significantly influenced by any of the factors **(Supp. Fig. S2)**. However, the distribution of the difference between these two timings, which characterize the movement duration (from the beginning of muscle activity to the keypress) revealed an intriguing pattern **(Fig. 5)**. The three-way repeated measure ANOVA for the tasks involving a keypress and a report revealed significant main effects of distance ($F(1,24) = 7.57$, $p = .01$, partial $\eta 2 = .24$), report instruction ($F(1,24) = 12.07$, $p = <.01$, partial $\eta 2 = .34$), and tone presence ($F(1,24) = 9.29$, $p = <.01$, partial $\eta 2 = .28$) on the percentage of trials with longer movement duration (between 0.1 and 0.5 s). In addition, the interaction between distance and tone presence was significant ($F(1,24) = 14.93$, p

< .01, partial η2 = .38). Finally, the interaction between distance, report instruction, and tone presence was significant (F (1,24) = 33.93, p < .001, partial η2 = .59), with significantly more trials for which the EMG activity started early (>0.1 s) before the keypress when the clock was closer to the body compared to when it was far in the decision baseline task only (Mean difference ± SE = 11.58 ± 2.36, p < .001, 95% CI [6.71, 16.46]). Finally, the paired t-test for the Action-only task did not show significantly more trials for which the EMG activity started early (> 0.1 s) before the keypress when the clock was near the body compared to when it was far (t (24) = 1.45, p = .16).

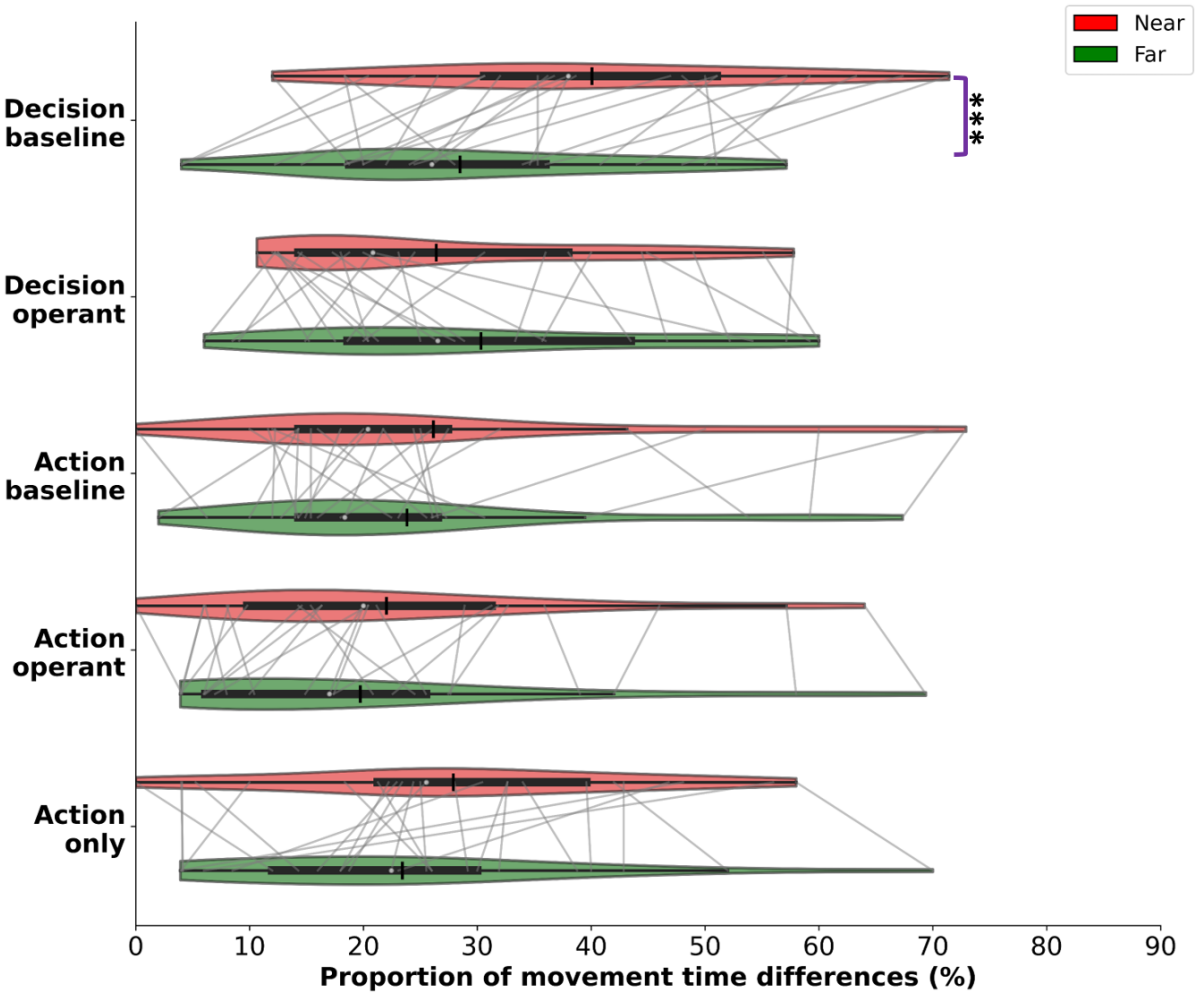

Figure 5. Proportion time differences between computer-registered keypress and EMG movement onset within the critical range of 0.1 to 0.5 s (note that the difference very rarely exceeds 0.5 s). The red and green violins distinguish between near and far distances, respectively. Each violin's width reflects the probability density of data points across the percentage of movement time differences on the x-axis, offering a visual portrayal of data distribution within each task. The white dot within each violin represents the median movement time, the thick horizontal line represents the interquartile range, and the vertical black bar represents the mean movement time within each task. *** for p < 0.001.

Discussion

This study investigates how spatial proximity, attentional focus, and anticipated action outcomes influence motor preparation and action awareness by exploring the impact of object

distance, report instructions, and action outcomes on the readiness potential (RP), while also analyzing subjective temporal perception and movement time during voluntary actions. EEG and EMG data were collected as the participants interacted with a Libet clock that was presented either close to or far from their body, in a virtual reality setting. Our results showed that shifting the focus of attention to the earlier phase - when participants reported the timing of their intention to act - enhanced the early RP, suggesting a stronger neural engagement in early preparatory activity. Additionally, shifting the attention to later phases, either by focusing on the action or by the mere-relevance of a task-irrelevant tone presented shortly after the keypress also influenced the RP by increasing the late RP slope. In cases where the tone was present, this effect was accompanied by a shift of the subjective reports of decision and action to later timing - a well-known temporal binding phenomenon (Haggard et al., 2002). Spatial proximity also influenced RP dynamics, specifically in tasks when participants focused on their intention to act in the absence of action-outcome (here, a tone). Behavioural findings further showed that when the clock was near, actions were perceived as occurring earlier compared to when it was far, suggesting a spatial influence on the temporal perception of action. EMG results showed that spatial proximity increased the likelihood of earlier-initiated and longer-lasting movements, particularly in decision-reporting tasks that lack action consequences. Below, we will discuss each of these main results in detail.

Focusing on decision timing (without subsequent action outcomes) enhances early RP amplitude and decreases the late RP slope, suggesting increased preparatory neural engagement during intention formation. In contrast, focusing on action execution leads to a steeper late RP slope, indicating a more rapid motor buildup when attention is directed toward movement onset. The stages of the early RP in the present study are more than 600 ms prior to the keypress, and between 600 and 200 ms prior to the EMG movement onset (given that most trials exhibit less than 400 ms between EMG movement onset and keypress). This places the early RP in the present study within the typical window between the RP onset and the W-time from Libet et al. 1983, which is traditionally considered as an unconscious stage of movement preparation (Armstrong et al., 2022; Libet et al., 1983; Shibasaki & Hallett, 2006). However, our findings importantly suggest that this unconscious stage of neural preparation phases (i.e. the early RP) is significantly influenced by the attentional focus on the intention to act. This indicates that modifications in RP are influenced not just by motoric demands, but also by the nature of cognitive engagement required by the task, challenging the view that RP is predominantly an unconscious precursor to voluntary movement. Early RP is believed to reflect general preparation for the impending movement, involving bilateral activation of the Supplementary Motor Area (SMA) (Oken & Phillips, 2009), which plays an important role during motor preparation and in controlling perceptual processing during voluntary actions (Nachev et al., 2008). Additionally, SMA activity increases when individuals focus attention on their intent to move, rather than on the movement itself (Lau et al., 2004). This suggests that SMA and pre-SMA activity may represent the intention (Haggard, 2005), a hypothesis supported by our observation of increased early RP when participants focused on their intention timing. Future research should thus aim to consolidate and deepen these findings, particularly exploring whether there is enhanced pre-SMA activity in scenarios like our decision estimation task, without subsequent action outcomes.

In this study, the locus of attention was manipulated by the instructions (reporting decision time vs. action time), but also by the presence or absence of a tone (action-outcome) following the keypress, even though the tone was task-irrelevant. In this context, we replicated the temporal binding effect: when a tone was present, both decision (which has received much less attention in previous studies) and action estimates shifted towards the tone, as observed in our earlier work (Kong et al., 2024). These decision-binding and action-binding effects were accompanied by an increase in the late RP slope, suggesting that anticipating an action outcome enhances the rate of neural buildup during the final stages of motor preparation. Interestingly, while previous studies have also shown that predicted sensory outcomes can modulate the RP, they typically report increases in RP amplitude rather than slope (Reznik et al., 2018; Vercillo et al., 2018; Wen et al., 2018). One possible explanation for this discrepancy is the absence of reporting demands in previous studies. Indeed, our results indicate that the type of report instruction significantly influenced the temporal dynamics of the RP. Another possible explanation might be the baseline correction procedures used in prior studies. Since baseline correction can influence RP amplitude measurements, it is important to recognize its potential impact on reported effects. Overall, our results suggest that the brain's preparation for action is not only about motor execution, but also encompasses the anticipation of sensory outcomes, as evidenced by an increase in the late RP slope, reflecting an integrated sensory-motor process. Understanding this relationship could have significant implications for designing cognitive and motor rehabilitation programs, particularly in disorders where sensory feedback processing is impaired. Future research could explore how varying the type and timing of sensory feedback influences RP, potentially leading to more effective rehabilitation techniques that leverage sensory-motor integration.

Our findings further suggest that the modulation of motor preparation by spatial proximity is task-specific, emerging prominently in the decision-reporting conditions. Specifically, late RP amplitudes were significantly greater when the clock was presented in near space compared to far space, indicating increased cortical excitability preceding voluntary movement. This enhanced motor preparatory activity is consistent with the notion that stimuli within PPS are prioritized by the brain due to their heightened relevance for bodily interaction and potential threat, thereby engaging sensorimotor systems more robustly (Blini et al., 2021; Bufacchi & Iannetti, 2018; Noel et al., 2015). Our behavioural findings showed that actions were estimated as occurring earlier when the Libet's clock was displayed in near space as compared to far space. This influence of the clock's proximity to the body on perceived action timing, despite no actual change in action initiation timing, replicates our previous findings (Kong et al., 2024). However, this spatial effect was absent in the perception of the tone's timing in the Tone-only task, suggesting that the modulation of temporal perception is associated with voluntary action rather than altering time perception in general. This could suggest that spatial proximity enhances the saliency of actions, thus accelerating subjective time perception related to these actions, and also further prompts the question of how spatial proximity may shape the subjective experience of agency, and whether this modulation occurs through perceptual, motor, or decisional mechanisms. EMG results showed that spatial proximity increased the likelihood of earlier-initiated but longer-lasting (slower) movements (i.e., muscle activities starting early before the final keypress) in a decision-reporting task without subsequent action outcome. These results might

indicate a generally earlier preparatory state under this task in the near space compared to the far space, aligning with the prior behavioral work of Blini and colleagues (2018), reinforcing the point that proximity to the body dynamically shapes sensorimotor engagement. Taken together, these findings emphasize the functional role of PPS not only in perception but also in voluntary action preparation and awareness. These results also highlight the necessity for further research investigating how proximity interacts with task demands, attentional states, and outcome expectations to modulate neural dynamics underlying voluntary action.

The debate surrounding the RP centers on its interpretation: whether it directly indicates the preparation for volitional action, is an artifact of random neural fluctuations, or reflects higher order cognitive processes. Schurger et al. (2012) significantly contributed to this discussion by proposing that the RP represents a decision-making process where spontaneous fluctuations in neural activity accumulate until a threshold is reached, thereby triggering action execution. This model challenges the traditional view of the RP as a straightforward precursor to voluntary movement, instead suggesting that it reflects a stochastic accumulation process. Alongside this, Schultze-Kraft et al. (2021) showed that the RP cannot be suppressed, even when participants consciously attempt to do so via a neurofeedback system while still performing voluntary movements, suggesting an obligatory component to its generation. Moreover, empirical studies have shown that the RP is influenced by various factors (Maoz et al., 2019; Travers & Haggard, 2021). Our study aligns with this perspective, revealing that attentional focus and action outcomes along with spatial distance, specifically, the proximity of a clock, modulates the RP in task-specific ways. These findings underscore the RP's sensitivity to situational variables, suggesting how certain contextual factors can influence neural excitability, bringing it to the action-triggering threshold, according Schurger et al.'s model, or modulating the temporal evolution and magnitude of motor preparation according to more traditional interpretations. Furthermore, the absence of a typical RP profile in our 'Tone-only' task, where participants estimated the timing of a randomly played tone, is compelling and suggests that RP-like events do not universally occur in scenarios lacking intentional actions (Travers et al., 2020). This observation reinforces the notion that the RP is intimately linked with the preparatory processes for intentional actions, rather than being a ubiquitous neural phenomenon.

Overall, this study discloses that attentional focus, action outcomes and spatial proximity each play a distinct and an interacting role in shaping RP and action awareness. The RP emerges as a highly flexible neural marker, adapting to task demands, internal higher cognitive processes and external environmental context, emphasizing how attentional focus on intention to act modulates early RP—traditionally considered an unconscious stage of neural readiness. Future research should further explore these dynamics across various voluntary action contexts, and how these factors interact with sense of agency and action decision-making processes.

Author Contributions

G.K. and A.F. led the conceptualization of the study. The study design was led by G.K., with supporting contributions from M.V. and A.F. G.K. took the lead in preparing the experimental setup and software, supported by B.B., C.D., and M.V. Data collection was conducted by G.K. and B.B. Data analysis was led by G.K., with support from B.B., A.F., and M.V. Data interpretation was led by G.K., with supporting roles from M.V. and A.F. The original draft was written by G.K. Revisions were led by G.K., M.V., and A.F., with supporting input from L.M. and F.P. All authors reviewed and approved the final version of the manuscript. Project administration was conducted by G.K.

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Ethics

This research complies with the Declaration of Helsinki (2023), aside from the requirement to preregister human subjects research, and received approval from a local ethics board (n°21-772, IRB00003888, IORG0003254, FWA00005831).

Data accessibility

All primary data, analysis scripts and materials are publicly available on the Open Science Framework repository (https://osf.io/tjus4/).

Conflict of interest declaration

None

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