Primed Action: Preserving Agency while Accelerating Reaction Time via Subthreshold Brain Stimulation

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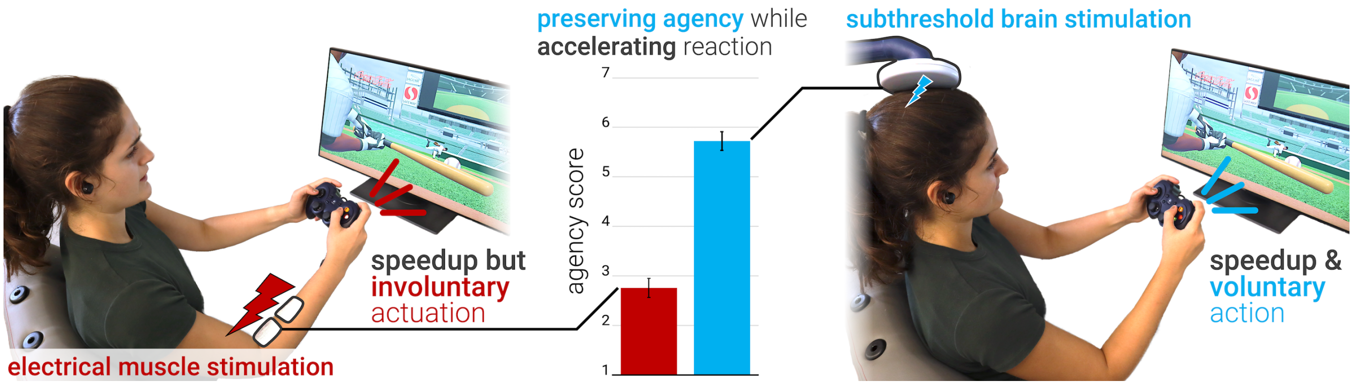

Figure 1: *Primed Action* is a technique to preserve users' sense-of-agency while accelerating their reaction. Unlike existing muscle-stimulation approaches that "force" users to react faster, Primed Action works below the threshold of involuntary movement—using subthreshold transcranial magnetic stimulation to prime the motor cortex. We found it preserved more agency than electrical muscle stimulation approaches (the error bars show 95% confidence intervals).

Abstract

While prior work in neuroscience confirmed that transcranial magnetic stimulation (TMS) can shorten the onset of muscle activity, the implications of this reaction-time speedup have not been explored in interactive systems. We present *Primed Action*, a novel interface concept that leverages this type of TMS-based faster reactions. What sets Primed Action apart from prior work that uses muscle stimulation to "force" faster reactions is that our approach operates *below the threshold of movement*—it does not trigger involuntary motion, but instead it "primes" neurons in the motor cortex by enhancing their neural excitability. As we found in our study, Primed Action best preserved participants' sense of agency than existing interactive approaches based on muscle stimulation (e.g., *Preemptive Action*). We believe this novel insight allows HCI researchers to implement new forms of haptic assistance that do not sacrifice agency, which we demonstrate in a set of interactive experiences (e.g., VR sports training).

CCS Concepts

• **Human-centered computing** → **Haptic devices**; • **Hardware** → **Emerging interfaces**.

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Keywords

Agency, Transcranial Magnetic Stimulation, Electrical Muscle Stimulation, Haptics

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1 Introduction

While people want to move their bodies as fast as possible in response to stimuli across contexts like video-gaming [12], competitive sports [3] to safety [70], there are limits to how fast we can react—in the case of audiovisual reaction, it is typically as high as 220~230 ms [20, 46]. To enable users to move faster, HCI researchers turned to haptic devices capable of involuntary actuation, notably, electrical muscle stimulation (EMS) [30, 40, 54]. EMS accelerates movement by stimulating muscles. However, to enable this speedup in reaction time, electrical impulses are sent before users send their own impulses [30]. As researchers have documented [6, 43], this has detrimental effects on user experience—users feel a "sharp loss of agency" [63] when stimulated to make movements that are not of their own volition (also, one cannot prevent an electrically-induced muscle contraction from occurring). Thus, while searching for ways to accelerate reaction time, it is paramount to improve users' agency. While researchers found that delaying the timing of EMS relative to a user's voluntary movement reduces some of the loss in agency

[30], this forces the user to move—as the researchers put it, "[the action] was externally generated by a haptic device and is aligned with the user's intention". We explore a fundamentally different approach we call Primed Action (Figure 1), where an interactive system accelerates users' reaction **without** forcing movements (i.e., no involuntary actuation). We achieve this using **subthreshold** stimulation applied to the brain's motor cortex via transcranial magnetic stimulation (TMS)—a safe and non-invasive brain stimulation using magnetism. The key technical insight is that we use just the right level of TMS intensity to increase excitability (i.e., how easily neurons can be activated) in the user's motor cortex, yet below the threshold of involuntary movement (Figure 2).

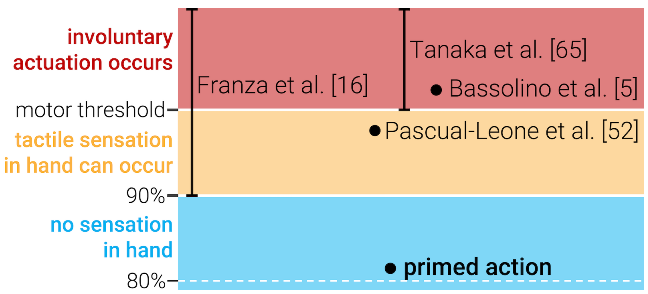

Figure 2: Overview of stimulation intensities used in related TMS research with respect to the motor-threshold & hand sensation threshold (~90% of the motor-threshold [16]). Unlike prior work, we opt for subthreshold of any hand sensation.

Using subthreshold stimulation, which has been shown to shorten the onset of muscle activity [52], it is possible to "prime" neurons to reduces the time it takes for the brain to generate the upcoming set of signals needed to execute a movement. Primed Action does this without resorting to involuntary actuation—it is the user who executes the action. As we found in our study, Primed Action best preserved participants' sense of agency than existing approaches based on muscle stimulation (e.g., *Preemptive Action* [30]).

2 Background and Related Work

Our work is motivated prior work that explored ways to reduce the loss of agency in accelerated reaction time. We also succinctly review transcranial magnetic/electrical brain stimulation techniques as they are relevant to our approach. The sense of agency here is defined as the feeling of control over one's movements (the sense of "I did that") [10, 72].

2.1 Haptic actuation causes a loss of agency

Any haptic device with sufficient force to move the body can accelerate it, but researchers have overlooked *what this does to users' sense-of-agency* [29], recognized as a key element in designing human-computer interactions [43]. Over the past decade of HCI, researchers confirmed that automated assistance during interactions can diminish users' agency [6]. Even a slight additional acceleration added to a user's GUI cursor reduces the sense-of-agency [11].

Most relevant is the fact that when researchers turned to EMS to physically speedup users' reaction time, they also found a loss of agency in this form of haptics [9, 30]. Even earlier interactive systems that made use of EMS reported subjective experiences from their users that hinted at this loss of agency. For instance, in *Affordance++* participants attributed agency to external objects rather than their own body when moved by EMS [40]. Similarly, participants in *PossessedHand* often felt out of control such as one who stated "I felt like my body was hacked" [64]. This loss of agency happens because if a user is moved via EMS before having formed their own intention of movement (or if the user-intended movement is *different* from the EMS-induced movement) it creates "a conflict between movements caused by [EMS] and the body's internal voluntary signals"—as denoted in Kruijff et al.'s seminal EMS work [35].

2.2 Adjusting timing reduces some loss of agency, but only if computer decision = human decision

The only approach available to tackle the loss of agency during haptic actuation has been to adjust the timing of when a haptic device actuates a user's body, a method proposed specifically for EMS-based devices [30]. Kasahara et al. investigated how modifying the timing of EMS affected users' agency while accelerating their reaction times in a standardized button press task [30]. They found that delaying the EMS stimulation closer to the voluntary button press, improved the sense-of-agency compared to EMS being triggered early. Also, they demonstrated that after training with this agency-enhancing approach, users' reaction time was *8 ms faster* even with EMS removed [31].

While these findings are promising, the same researchers reported that this method is *significantly less effective when the interface's and user's intentions are not aligned* (e.g., when the user decides *not to press* a button) [63]. Additionally, EMS inevitably induces unwanted tingling sensations that have been shown to reduce comfort [66]. More importantly, this approach does not change the fact that users are being *forced to move when the device wants*, not when the user wants, as the authors stated "our preemptive action [...] never provided a sense of complete agency" [31].

2.3 Transcranial magnetic stimulation (TMS)

Our approach *primes* user's brain to be faster at reacting. Thus, we succinctly review transcranial magnetic stimulation (TMS)—our technique of choice.

While other techniques exist for brain stimulation (e.g., ICMS [15], tDCs [49], or tACs [24]), TMS has gained popularity in neuroscience due to its selectivity and non-invasiveness [22]. TMS uses a coil to produce an oscillating magnetic field that creates small electrical currents inside the brain [22]. The main applications for TMS are in research (e.g., map brain functions to cortical areas [71]) and depression therapy [19].

Related to our proposal, TMS applied to the motor cortex can create downstream effects by modulating neuronal excitability in that region [22, 51], often observed through differences in muscle activity (e.g., altering observed EMG amplitude [69]). Indeed, Pascual-Leone et al. demonstrated that TMS could modulate the onset time of muscle readings [52], which is a key insight that our approach leverages.

Only recently was TMS used for human-computer interfaces: Bassolino et al. demonstrated that TMS to the motor cortex improved the sense of embodiment in a VR rubber hand illusion [5]; Novy et al. explored interactive visual perception through the stimulation applied to the visual cortex [50]; Tanaka et al. repurposed TMS stimulation for muscle-based force feedback [66]; finally, TMS was shown to create force & tactile feedback for VR [65]. As shown in Figure 2, these TMS applications use *supra-threshold* TMS, i.e., generate involuntary movements.

2.4 Subthreshold brain stimulation

Subthreshold *electrical* brain stimulation (e.g., tDCs) is also possible. In these techniques currents travel inside the cortex via electrodes attached on the scalp. Unfortunately, they have not been shown to have any effect on motor reaction time, according to Horvath et al. [25], which exhaustively studied a wide range of subthreshold stimulations with tDCs. Conversely, these have been used for enhancing perception in VR. For instance, Langbehn et al. used tDCs to reduce disorientation in VR walking [36], and Škola et al. found that tDCs increases the sense of ownership over a VR avatar [73]. It is worth underscoring that even if electrical brain stimulation approaches such as tDCs would have an effect on reaction time, these usually require from 15-20 minutes of stimulation for observable effects [36, 73]. In contrast, our TMS-based approach uses a single 320µs pulse, which can *already* prime the cortex for an observable speedup.

3 User Study: Sense of Agency & Reaction Time

To validate Primed Action, we conducted a controlled user study where we measured participants' sense-of-agency while they were performing a series of standard reaction-time trials either with *Primed Action* or baseline conditions (*sham-TMS* and *EMS*). As in prior work in HCI, "agency" here was defined as the feeling of control over one's movements (the sense of "I did that") [10]. The study was approved by our Institutional Review Board (IRB21-0055).

3.1 How our study provides new HCI knowledge

While prior work in neuroscience already confirmed that TMS can shorten the onset of muscle activity [52], our study is the first to investigate *agency* when primed by interactive TMS. Thus, we tailored our TMS intensity to work below the threshold of involuntary muscle contractions *and* below the threshold of any hand sensation [16] since feeling tactile sensations in one's hand would diminish users' sense-of-agency, as confirmed by [30]. Thus, as illustrated in Figure 2, our TMS intensity was much lower than that of [52], which utilized just below the involuntary contraction threshold which is *still strong* and generates tactile sensations [16].

It is also worth noting that our study measured reaction times against the *entire interaction*—from an on-screen stimulus to a button press, i.e., an actual interface-level input. This was to capture an end-to-end process of a user's reaction in an interactive context: (1) the user's muscles have to sustain contraction until they start moving the joint, (2) then, they must keep applying force until it exceeds an interface's input-detection threshold, e.g., mechanical buttons, touchpads, and EMG-based controllers; they all require such thresholds and are therefore not instantaneous, even for brief inputs. By evaluating reaction time as the end-to-end time required to complete an interface input, our study encompasses all latency associated with human movement during interaction and translates better to how HCI designers can leverage our approach.

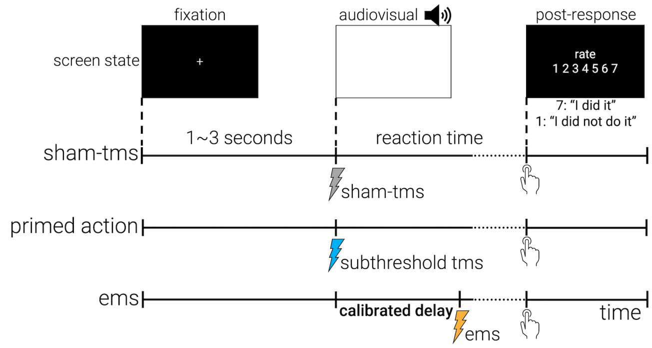

Figure 3: A summary of our task & procedure.

3.2 Conditions

Primed-Action. We stimulated participants' left motor cortex (corresponds to right arms) with a single subthreshold TMS pulse (320µs, common in TMS literature [5, 16, 68]). As shown in Figure 3, the stimulation timing aligned with the audiovisual-reaction stimulus, accounting for the latency (similar process to [52]), i.e., no per-participant calibration.

Sham-TMS. As TMS causes a "clicking" sound and slight tactile sensation on the scalp, we accounted for them as confounding factors, i.e., simply adopting a no-stimulation baseline would not allow us to quantify *how priming the motor cortex affects reaction times.* Thus, we applied TMS at equal intensity/timing (no timing calibration) as *Primed-Action* to a different brain region *unrelated to movement* (denoted as the P3 region—a common area in TMS studies that use sham stimulation [8, 52, 68]). This condition acted as a baseline to evaluate participants' voluntary reactions.

EMS. We replicated *Preemptive Action* [30], with a single 400µs pulse of EMS. To enable a fair comparison of the perceived agency across *Primed-Action* and this condition, we calibrated the preemptive delay in the EMS timing.

3.3 Study design

Participants. We recruited 12 participants from our institution (8 identified as male, 4 as female, average age=23.8 years, SD=2.3). All participants were right-handed. Participants were compensated with $30 USD.

Task. We adopted a simple reaction-time test (Figure 3). This was chosen to depict the best-case scenario for EMS, since in this task, both the participant and the EMS had their intentions *aligned* (press one single button—no decision). Since it is already known that EMS accelerations dramatically reduce agency if the task involves decisions (e.g., Stroop test [63]), we opted for the simple reaction test to favor the EMS. Per trial, we instructed the participants to press a key as fast as possible upon an audiovisual stimulus (500Hz beep simultaneous with the screen turning white; as in [38]). The delay of the audiovisual stimulus was randomized between 1~3 seconds.

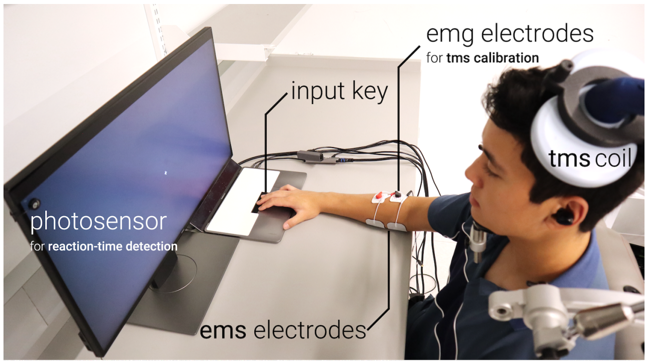

Figure 4: Our study setup.

Upon tapping, the screen turned dark and the participants rated agency on a Likert scale (1="I did not do that"; 7="I did that")—a measurement employed widely in HCI [7, 30, 61] and already shown to be correlated also with an indirect measure of agency [27]. It is worth noting that both direct and indirect measures are currently considered valid metrics of agency [44].

Apparatus (Figure 4). We used a Magstim D702 coil on a tripod, connected to a Magstim SuperRapid2 TMS stimulator. To monitor muscle activity during TMS intensity calibration, we measured wrist-extensor (*extensor carpi radialis*) EMG with a TMSi SAGA—a typical approach in TMS calibration [41, 59], connected to an amplifier. The participants wore a pair of EMS electrodes on the ring finger's muscle (*flexor digitorum profundus*) connected to a HASOMED Rehastim1 EMS stimulator. Audiovisual feedback was presented via a display and noise-cancelling earphones. A photosensor attached to the display detected color changes and was connected to a separate input channel of the amplifier, to measure reaction time at 4000Hz. Finally, we controlled TMS using MagPy Toolbox [42][1]. End-to-end latency (until stimulation) was 16 ms for TMS and 12 ms for EMS measured via a high-speed camera.

Procedure. At the beginning, we obtained informed consent. Then, participants performed 20 trials of the reaction-time test without stimulation or ratings. Then, we calibrated the TMS and EMS, as described below; this process was conducted only once. Next, each participant completed a total of 60 trials: 3 conditions × 20 repetitions, with counterbalanced condition order (Latin square). Study took ~60 minutes, including 2-minute breaks (extended upon participants' request) between calibration/condition blocks.

Calibration for stimulation. Prior to the trials, we calibrated TMS and EMS. For TMS, the experimenter adjusted the coil position using the grid-search method [32] while modulating the stimulation intensity based on Awiszus' method [4]. The calibration was completed once they identified the lowest intensity that evoked an EMG response (motor evoked potentials), i.e., motor-threshold. We then lowered the intensity by 10% of the stimulator's maximum output to ensure that TMS remained subthreshold—the experimenter confirmed that no EMG activity was observed. Additionally, we confirmed with the participant that no hand sensations were felt with TMS. For EMS, the experimenter followed the procedure from [67]—adjusted the electrodes and the minimum intensity that robustly caused the ring finger to involuntarily tap the key.

[1]https://lab.plopes.org/#primed-action

Calibration for EMS timing. While neither of the TMS conditions required calibration of the stimulation timing, we controlled the acceleration of the EMS condition. This is because agency under EMS decreases sharply, e.g., users no longer felt in control of their actions (rated as "0" agency) in 50% of trials with an acceleration of ~40 ms and it drastically dropped as the timing got even earlier [67]. As such, we adjusted the timing of the EMS preemption to result in a comparable speedup to that of Primed Action. To this end, participants performed 10 calibration trials of reaction time with Primed Action. From their average reaction time in these calibration trials, we adjusted the EMS preemptive timing by subtracting 50 ms (the time for EMS to actuate fingers to tap [30, 48]). We then performed 10 calibration trials of EMS to confirm or re-adjust until the result was comparable. For instance, if during calibration a participant reacted with an average of 210 ms with Primed Action, we set their EMS to start at 160 ms (210 − 50) after the reaction-time stimulus. Note all calibration trials were then discarded and not part of the main study. Moreover, note that the sham-condition was only part of the main study, not of the calibration trials; as such, both reaction times and agency scores were only examined using data from the main study (i.e., when all three conditions ran in their counterbalanced order).

Calibration data. Our participants were calibrated to an average TMS intensity of 43.2% (SD=6.7) on the stimulator's output, i.e., 80.9% (SD=2.4) of their motor-threshold (this is the ~80% we depicted in Figure 2). In EMS, our participants were calibrated to an average intensity of 9.3 mA (SD=0.8) and preemptive-timing of 116.4 ms (SD=5.8).

Safety. Since TMS [57] and EMS [33] could interfere with implanted devices (e.g., pacemakers), we did not recruit such participants. According to the safety & ethics guidelines for TMS released in 2021 [57], when TMS was applied to non-epileptic users, no lasting adverse events (e.g., seizures) were reported. This is supported by a comprehensive review of TMS, including long-term use of up to 26 months [37]. We included an emergency-s op switch in our study apparatus (no participants resorted to it). We adopted a five-second break between trials as suggested by [58], which ensures safety on single-pulse TMS, even at supra-threshold.

3.4 Results

Figure 5 shows our key results contrasting *Primed-Action*, *sham-TMS*, and *EMS* with regard to participants' reaction time and sense-of-agency. Through Shapiro-Wilk, we found that both the reaction times and agency scores violated normality. Upon this violation, a Friedman test can be used to model the effect of conditions in a non-parametric manner by averaging responses from trials per participant [30].

	reaction time (ms)		agency score	
	mean	SD	mean	SD
sham tms	209.0	45.6	6.0	1.3
primed action	201.1	47.9	5.7	1.5
ems	201.0	31.7	2.8	1.5

Figure 5: A summary of reaction times and agency scores.

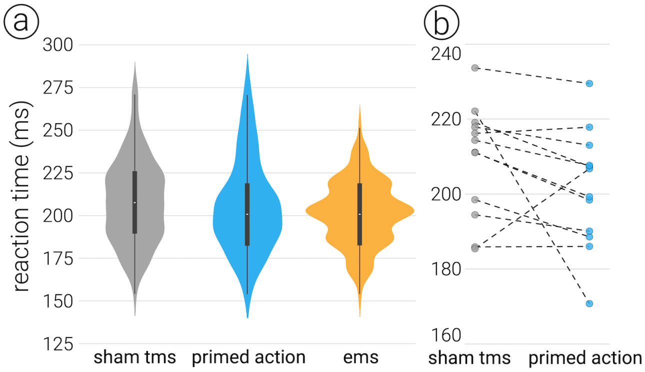

Figure 6: (a) Reaction-time distributions. (b) Participant-level breakdown of reaction times (*sham-TMS vs. Primed-Action*).

The Friedman test indicated a significant effect of condition on agency scores ($\chi^2(2)$=18.7, p<0.001), but not on reaction times ($\chi^2(2)$=4.7, p=0.097). Figure 6 shows the reaction-time distributions.

As shown in Figure 7, Post-hoc pairwise comparisons via the Wilcoxon signed-rank test showed significant differences in agency scores for *sham-TMS vs. EMS* (Z=−3.1, p=0.001) and *Primed-Action vs. EMS* (Z=−3.1, p=0.001) but not for *sham-TMS vs. Primed-Action* (Z=−1.9, p=0.19)—all comparisons were Bonferroni-adjusted.

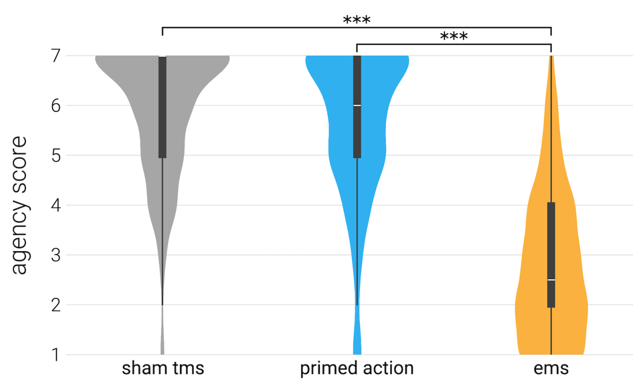

Figure 7: Agency-score distributions.

3.5 Discussion

To allow other researchers to run their analysis using any alternative methods they see fit, we made our data public[2].

Large improvement in the agency. We found that participants rated their agency substantially higher for *Primed-Action* compared to *EMS*. Note that the EMS was delayed close to the participant's reaction time—considered the best case for EMS agency [30, 63]. With *Primed-Action*, participants were not involuntarily actuated, which we believe is the primary cause of this improved agency—with Primed Action, they feel that they are *the cause of the action* [72]. On the contrary, our EMS baseline yielded lower agency than *Preemptive Action* [30]. As in most studies of this nature, "absolute values" do not easily generalize because ratings are made in relation to each study's baseline conditions. Importantly, *Preemptive Action* [30] employed multiple EMS-based baselines (one EMS condition without delay and one "EMS-only" baseline where participants were instructed not to move). In contrast, in our study, the participants compared the EMS condition against conditions that do not involve any involuntary movements (*sham-TMS & Primed-Action*), which certainly leads to lower agency during EMS. Moreover, a recent replication of *Preemptive Action* [47] demonstrated that absolute agency ratings for a single EMS condition can even vary between two sub-experiments, likely due to differences in conditions and setups.

Possible effects on reaction time. While the Friedman test (modelling only conditions as a factor) did not find an effect between conditions for the reaction times, prior work in neuroscience has demonstrated that TMS can shorten the onset of muscle activity [52]. One way to probe this gap is to account for trial-level variability, which we present in our **Appendix**[3] by modelling both factors (trial-level variability and conditions). This alternative analysis suggests consistency with the findings that TMS shortens the onset of muscle activity [52] with a speedup of ~8 ms (see Appendix).

Sham-TMS did not perfectly preserve agency. *Sham-TMS* did not always result in full agency. Similar to the sham-EMS conditions from [30], this may be due to the side-effects of TMS, i.e., the clicking sound or tapping sensation on the scalp. While these side effects have no effect on movement, it is possible they distracted the participants in some trials.

Study limitations. First, our sample size (N=12), while typical for psychophysical studies in this domain, may not capture the full spectrum of responses. Second, our study design measured natural reaction time without training, which led to modeling the effects of trials (e.g., possible learning effect) and reaction time. Alternatively, one could design study variants that include training sessions prior to the experiment to reduce trial-level performance variance among participants (e.g., <10%).

4 Envisioning Areas of Application

In the following, we envision some exemplary applications that make use of Primed Action. We implemented functional demos on Unity3D, which communicates to our Python TMS controller via Open Sound Control (OSC), and with application-specific input modules (e.g., gamepad). Note that these applications are envisioned as a future training platform and not to replace human skills.

4.1 Competitive eSports

Primed Action might be able to assist in eSports (a domain where small speedups can affect a game's outcome [45]). Figure 8 depicts a user sitting on a chair, which allows for TMS instrumentation, playing our baseball game where Primed Action assists with batting. The user gains a small fraction of time to observe the ball's trajectory and decide when to press with better timing to hit the ball. By preserving agency, this assistance might interfere less with the user's enjoyment—critical in gaming [60]. To detect the input with a resolution compatible with eSports, we use a wired gamepad (Logitech F310) paired to our Python instance (at >1000Hz).

[2]Dataset at https://lab.plopes.org/#primed-action and in the supplementary material.

[3]Appendix at https://lab.plopes.org/published/2025-UIST-PrimedAction-Appendix.pdf

Figure 8: Primed Action assists the user's performance in a baseball batting game without compromising their agency.

4.2 VR sports with a wearable TMS interface

Figure 9 depicts a more wearable form factor of Primed Action. We engineered our device by replicating an open-source VR-mounted TMS device [65] and further improved its wearability by adding a shoulder brace to distribute the load. Here, Primed Action allows a user to play a competitive VR ping-pong, speeding up their hitting time. The fact that Primed Action does this without compromising agency might positively affect training experiences [31, 55]. For the implementation, we attached an IMU (MPU6050) to the paddle to track it at ~1000Hz.

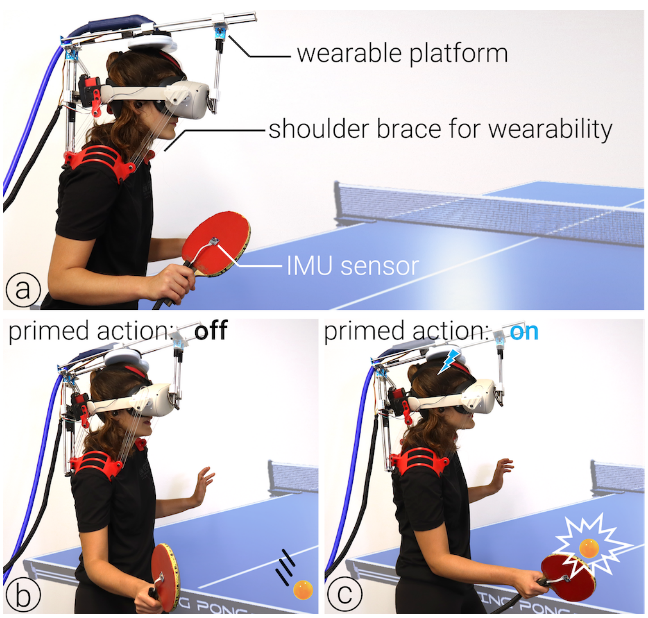

Figure 9: (a) A wearable version of Primed Action for ping-pong. (b) The ball speed is set to be faster than the user's reaction, making it hard to hit. (c) With Primed Action, the user is more likely to hit the ball they would normally miss.

5 Limitations and Future Work

5.1 Limitations

Conceptual limitations. Our advantage of not inducing involuntary actuation is also our limitation: Primed Action is, technically, not an actuation technique as it cannot induce involuntary movement, it can only speedup voluntary movements. Thus, Primed Action cannot be used for situations that require force feedback. Additionally, because Primed Action does not force movements, it can only excite neuronal activity enough for a slight speedup and cannot create large speedups unlike the ones with EMS (achieved by largely disregarding agency).

Form factor. While a TMS coil can be made wearable in some cases (e.g., integrated into VR headsets [65]) it is still more cumbersome than EMS. However, it is worth noting that Primed Action only uses ~50% stimulation intensity of our current device, thus, it is likely to achieve comparable results via a much smaller 35 mm coil [13]. Moreover, it is possible to engineer a custom TMS devices as an alternative to commercial ones that are currently bulky. For instance, the latest state-of-the-art wearable TMS system measures just 17×14×6 cm and weighs 3 kg in total [56].

Acoustic and tactile noise. TMS is accompanied by a short "click" sound of ~55 dB (smaller than propeller-based devices, e.g., 83 dB [28]) at the average intensity from our study [34]. Fortunately, it has been demonstrated that advanced coil casing can reduce this by ~19 dB [53]—as these authors stated, further optimization and reduction are possible. Finally, it is also accompanied by a slight tactile sensation on the head.

5.2 Future work

Broader understanding of user experience. Since our study's central objective was to evaluate the sense-of-agency in Primed Action, we used the Likert-scale question as our measure, following prior work across HCI, cognitive science, and neuroscience [17, 30, 62]. Future work might explore additional aspects of user experience (e.g., body ownership [2], cognitive load [23], sensorimotor congruency [1], intentional binding [44], and sensory attenuation [26]). As another direction, comparing Primed Action to supra-threshold TMS could provide insights into how different involuntary actuation might affect agency. Moreover, our applications were intended to succinctly illustrate more diverse uses of Primed Action rather than to supplant future evaluations of the user's experience of new interactive contexts. For instance, researchers might explore if the preserved agency also shapes motivation, or enhances training as with EMS [31].

Applications with an advanced TMS from factor. Recent improvements in TMS hardware [56] might be able to bring applications previously only demonstrated with EMS to Primed Action. One such application is skill assistance, e.g., helping a drummer with hitting notes on time [14], while still preserving their sense of control over the performance.

Primed Action in decision tasks. Because Primed Action does not force a user to move (i.e., it keeps a user's "intention" intact [21]), it is likely that future studies might find it supports applications that involve decision making. As depicted in Figure 10, we expect that Primed Action preserves sense-of-agency regardless of whether the user's intention aligns with that of the interface. Future work

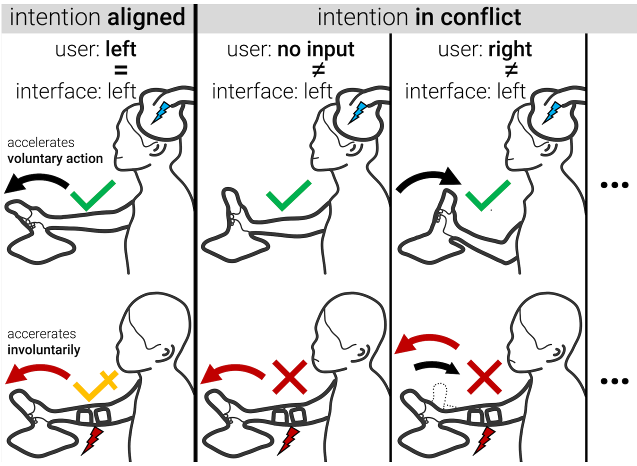

Figure 10: Contrasting agency when using an input device (e.g., joystick) with Primed Action vs. EMS under "intention-aligned" and "intention-in-conflict" (terminology from [63]).

could evaluate this by comparing Primed Action vs. EMS vs. a no-stimulation baseline in decision-based tasks.

Figure 11 depicts an envisionment of decision-based applications: the user controls a flight simulator and chooses to fly their plane left/right. We expect that this type of application of Primed Action is beneficial in that users always preserve agency, additionally, if their intention aligns with the interface's, they experience a speedup. This is a contrast to EMS forcing users' outcome during speedup Figure 11 (c), resulting in low agency [63].

Figure 11: Envisioned use of Primed Action with decision tasks.

Predicting intention. Primed Action lends itself well when the timing of events is known or easy to estimate from the standpoint of the interactive system (e.g., our eSports application). However, predicting users' intentions remains an open challenge [39]. A promising direction is integrating sensing for intention prediction. For instance, Gherke et al. integrated EEG to predict when to accelerate reaction time; yet the accuracy remains a challenge [18].

6 Conclusions

We introduced Primed Action to unveil a way to preserve user's agency during accelerated reactions. Our concept leverages the fact that it is possible to prime neurons of the motor cortex but without causing any involuntary movements. We found evidence that unlike prior work that used muscle stimulation to "force" faster reactions, our approach provides more sense-of-agency. We believe these insights open the door for HCI researchers to develop new forms of haptic assistance that preserve agency, as demonstrated in our proposed interactive applications.

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