Whose touch is this?: Understanding the Agency Trade-off Between User-driven touch vs. Computer-driven Touch

DAISUKE TAJIMA, Sony Group Corporation, Sony Computer Science Laboratories, Inc., Japan
JUN NISHIDA, University of Chicago, United States
PEDRO LOPES, University of Chicago, United States
SHUNICHI KASAHARA, Sony Computer Science Laboratories, Inc., Japan

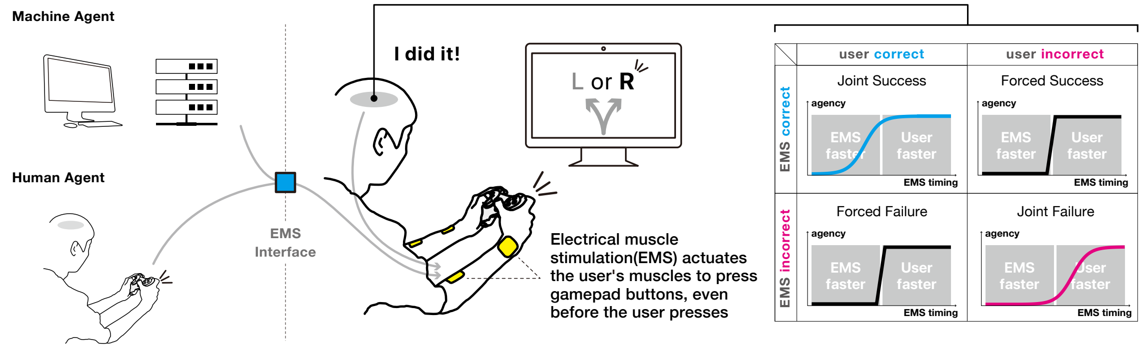

Fig. 1. The paradox of adding force-feedback to digital touch systems is that the haptic device needs to *force* the user to touch, faster than they normally would—so that the resulting touch is *computer-driven*, rather than *user-driven*—while this can have a range of benefits, it unfortunately also causes *users to lose their sense of agency*. To contribute to the improvement of digital touch systems, we investigated how the user's sense of agency changes when their own touches are assisted by electrical muscle stimulation (EMS). We went deeper than previous work by investigating situations where the user *has a choice on how to touch* (see matrix). For instance, we investigated what happens not only when the user-driven touch and the computer-driven touch are aligned (joint success), but, more importantly, explored when the computer-driven touch forces the user into an outcome they did not intend (forced failure or a joint failure), or conversely, when the computer-driven touch forces the user in an outcome they would not achieved alone (forced success). We found different agency-profiles depending on whether the user-driven touch or the computer-driven touch is congruent or not; as such, does the timing of the computer-driven touch influence the sense of agency, but the outcomes affect agency too.

Abstract: Force-feedback enhances digital touch by enabling users to share non-verbal aspects such as rhythm, poses, etc. To achieve this, interfaces actuate the user's to touch involuntarily (using exoskeletons or electrical-muscle-stimulation); we refer to this as computer-driven touch. Unfortunately, forcing users to touch causes a loss of their sense of agency. While researchers found that delaying the timing of computer-driven touch preserves agency, they only considered the naïve case when user-driven touch is aligned with computer-driven touch. We argue this is unlikely as it assumes we can perfectly predict user-touches. But, what about all the remainder situations: when the haptics forces the user into an outcome they did not intend or assists the user in an outcome they would not achieve alone? We unveil, via an experiment, what happens in these novel situations. From our findings, we synthesize a framework that enables researchers of digital-touch systems to trade-off between haptic-assistance vs. sense-of-agency.

CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)**; *Haptic devices*; User studies.

Manuscript submitted to ACM

Additional Key Words and Phrases: touch, haptics, proprioception, agency, electrical muscle stimulation, automation, tactile

ACM Reference Format:

Daisuke Tajima, Jun Nishida, Pedro Lopes, and Shunichi Kasahara. 2021. *Whose touch is this?*: Understanding the Agency Trade-off Between User-driven touch vs. Computer-driven Touch. In . ACM, New York, NY, USA, Article 1, 27 pages. https://doi.org/10.1145/3489608

1 INTRODUCTION

While we typically think of *touch* as a depiction of haptic qualities such as contact & texture, recent advances in force-feedback compel us to also consider the challenge of *assisted-touch*, i.e., a touch that is driven by the computer interface via force feedback, which causes the users to touch their user interface involuntarily—we refer to this emergent type of haptics as *computer-driven touch*.

On one hand, the addition of computer-driven touch to digital touch systems greatly enhances not only the sense of immersion but also interpersonal communicative capacity by enabling users to communicate non-verbal aspects such as touching/tapping to a rhythm [60], speeding up users reaction times in a touch-based interaction [31], sharing poses with a remote user [59], and even sharing emotions [25]. To deliver this type of proprioceptive information to their users, haptic interfaces actuate the user's body, typically via exoskeletons [27, 46, 63, 78] or electrical muscle stimulation (EMS) [42].

On the other hand, to realize computer-driven touch, these haptic interfaces need to actuate the user's body by moving it, even against the user's intention. In fact, to provide users with these benefits (e.g., speeding up users' reaction times in touch-based interactions [31]), these devices *need to actuate the user's to touch faster than they normally would*—they force users to touch *preemptively* (otherwise, the user would finish the touch and not benefit from the improved outcome via the haptic assistance) [31].

Unfortunately, *forcing* the user to move causes *users loose their sense of agency* (i.e, the sense of control of one's body) [4, 31, 51], which is particularly detrimental to both digital touch and interpersonal communication systems.

Moreover, while there are efforts designing and engineering haptic devices capable of actuating the user's body, the efforts focused on understanding this loss of agency and even engineering devices that mitigate this loss of agency are virtually nonexistent. As such, there is a critical, yet unanswered, challenge associated with the advent of computer-driven touch: *Whose touch is this?* or, in other words, *to whom will users attribute these computed-driven touches? To themselves or to the UI?*

One promising approach to improve the lack of agency has been revealed recently, as researchers found out that adjusting the timing of the computer-driven touch allows users to feel more in control [31]. In other words, delaying the computer-driven touch timing to be closer to that of user-driven touch has been shown to preserve some of the user's sense of agency, even when externally moved by means of a haptic device, such as an EMS-based interactive device [31]. However, this prior work only considered the naive case in which the computer-driven touch is aligned with the user-driven touch (joint success).

We argue that this is actually a rather unlikely case because it only works when we can predict what the user's touch will be, which is notoriously difficult and has eluded decades of HCI/Neuroscience research [48, 66]. So, what about all the remaining and more frequent situations depicted in Figure 1? For example, when the computer-driven touch forces the user into an outcome they did not intended (forced failure or joint failure), or, conversely, when the computer-driven touch assists the user when they would have made a mistake by themselves (forced success). To reveal what happens at the intersection of the user's agency and computer-driven touch, we explore, by means of an experiment, what happens precisely in these **novel situations in which the user actually has a choice** and thus the UI might correctly or incorrectly provide adequate or inadequate haptic assistance.

As such, in this article, we make a systematic attempt to understand the loss of agency in haptic interfaces and propose methods designers can employ to mitigate these effects, allowing designers to effectively build better haptic systems that can prioritize and/or trade-off between the user's sense of agency vs. haptic assistance. We conduct our investigation of this loss of agency by using electrical muscle stimulation as the ideal case-study since its loss of agency in computer-driven touch is well-known and, simultaneously, many see this stimulation technique as a promising approach to wearable haptics.

To understand the trade-offs between the user's sense of agency and computer's haptic-assistance, we engineered a novel variation on the Stroop test [26, 50, 77], in which we introduced EMS as the computer-driven touch. In our experiment, participants answered two-choice questions by tapping with either hand. Not only could they always try to choose the correct answer voluntarily (user-driven touch), but an EMS device was engineered to also simultaneously actuate their hand to answer (computer-driven touch) slower and/or faster than the user's own reaction. As such, we were able to make the haptics play two distinct roles: (1) assistive-touch (which will result in joint success or forced success) or (2) adversarial-touch (forced failure or joint failure). Then, our Stroop experiment allowed us to investigate the sense of agency in the four quadrants of computer-driven and user-driven touch. We found that the **participant's attribution of action was more biased by the positive outcome**, in which computer-driven touch and user-driven touch were congruent. In contrast, in incongruent-touches, the attribution of action was clearly distinguished depending simply on whether user-driven touch or computer-driven touch was faster to complete the task.

From our findings, we ultimately synthesize a framework that we then illustrate using a set of exemplary applications. We expect that these examples, together with our underlying framework, will enable researchers, designers, and practitioners of future digital touch systems to prioritize or trade-off between the user's sense of agency and the computer's haptic-assistance.

2 RELATED WORK

Our work builds primarily on the areas of digital touch, with particular emphasis on proprioceptive haptics using actuators such as exoskeletons or electrical muscle stimulation (EMS). Furthermore, our investigative focus on agency has its root in contemporary theories of the sense of agency originating from neuroscience and cognitive psychology.

2.1 Sense of agency

The sense of agency, which we define as the user's sense of control over their own body, is a neural mechanism that drives one's awareness of initiating, executing, and controlling our own voluntary actions in our surroundings [29]. The sense of agency allows us to recognize ourselves as the agent of a particular behavior, enabling us to build a self that is distinct from the external world [29]; it is thus considered one of the most primal mechanisms of the human experience. Furthermore, while some conceptual HCI frameworks (such as [19, 53]) also consider the agency of an interactive computer system, we focus solely on the agency of the user in our investigation.

In the field of neuroscience there are different views that suggest a neural mechanism for handling the sense of agency. One view, which is of relevance to our research, places the motor system (i.e., the neural apparatus that controls voluntary movements) at the center of the question of agency [21]. Support for this comes from, for example, the experiments conducted by Frith et al., where it was revealed that participants with lesions on the motor cortex (but no lesions on the sensory organs or pathways that allow to feel touch, etc.) exhibited a decreased sense of agency [21].

This theory states that the agency is dependent on the comparison between the prediction of a movement and its **outcome**–as we will later see, this plays a key role in our investigation as haptic devices can change the outcome of the action in ways the user did not intend, e.g., in false-positives cases, where the device incorrectly predicts the user's intention. Through our studies, we validate an interaction between outcome and the sense of agency, which we then use in our techniques for preserving agency even for systems that move users by means of EMS.

Moreover, while much is still not understood regarding the inner workings of our sense of agency, we do know that **the sense of agency is not a static and immutable state**, as many experiments have shown such as in the rubber hand illusion [7, 36, 76], randomly generated feedback [17, 30], inversion of user's movements [30], distortion of the haptic feedback [74], deception [61], and delays or speed-ups in feedback [17, 30].

As such, by **drawing from neuroscience and cognitive psychology, we were able to leverage two interactions between the user's sense of agency and two properties of the haptic interface** that we postulated would assist HCI designers in preserving the user's sense of agency, even when users are moved so as to touch involuntarily by a haptic interface (e.g., EMS). These were **(1) haptic/touch timing** (when does the haptic device start to move the user); and **(2) expected outcome of an action, such as a touch on a computer-interface**–we succinctly present the neuroscientific basis of each below.

2.1.1 Interaction between touch/movement timing and the sense of agency. A series of studies has shown that the perception of time is one of the elements that create the degree of association between a voluntary action (our intention) and outcome (the result of our intention); this has been shown to drive the sense of agency by Libet et al. [35] and Haggard et al. [23]. These findings (e.g., Libet's clock experiment) found the existence of a time delay between a volitional action and our sense of agency for this action [47]. One key conclusion of all these studies in neuroscience is that "temporal sensorimotor discrepancies reduce the sense of agency" [14]. This has been shown by offsetting the onset of the expected outcome in visual, tactile, or auditory modalities [17]. Thus, time is a key in preserving the sense of agency. We argue that this is the parameter that preemptive interactive systems must tune in order to provide more agency to their users.

2.1.2 Interaction between action outcome and the sense of agency. Secondly, not only does the sense of agency interact with the timing of one's action but, moreover, researchers in neuroscience have found it to also interact with the expected outcomes of one's action. For instance, Yoshie et al. found that the emotional beep sound (e.g., negative like fear sound and positive like achievement sound) caused by the participant action could modify the sense of agency [79]. Barlas et al. found that the ease of expectation of the outcome boosts the sense of agency [3]. This interaction between our sense of agency and our expected outcomes of a motor action is especially important for real usage of an interactive system because users are *free* to act out their *intentions* (e.g., one can choose where to tap, which button to click, etc). However, when haptic systems can move the user's body so as to generate touches for the user (such as what has been achieved with exoskeletons or EMS), this matter is further complicated as the computer system is now able to actuate the user into outcomes that the *user might not be able to predict or be interested in.*

We argue that this is the crux of the agency question because UIs cannot predict the user's intention accurately; in fact, this is known to be notoriously difficult and has eluded decades of research. For instance, in neuroscience, many argue this is a hard challenge for the field (e.g., "there is no evidence that the outcome of more complex free decisions can be predicted from prior brain signals" [66]); similarly, some consider predicting outcomes the "holy grail" of sports medicine [48]—still, no interactive system has shown how to accurately predict complex user intentions.

2.2 Efforts in HCI to understand the user's sense of agency

When designing interactive systems, the sense of agency is key to achieve a user experience that grants a sense of *control* to the user. Unfortunately, achieving this becomes more challenging with assistive systems that automate the user's behaviour in any way (haptic or otherwise). This has been observed for UIs that automatically change the system to facilitate interactions [49, 51]. For instance, Coyle et al. found that changing the amount of assistance the interactive system provides to the mouse cursor that the user is manipulating (e.g., via predictive mouse acceleration) had a significant impact on the user's sense of agency [13].

In fact, understanding the user's sense of agency in modern UIs is so crucial to designing interactive systems that the HCI community has been deepening its understanding of it: McEneaney et al. found that machine-induced mouse clicks affect the user's perceived agency [49]; Coyle et al. found that the mouse cursor speed manipulations can affect agency [13]; Bergstrom-Lehtovirta et al. found that on-skin interaction improves the sense agency vs. a traditional button press [5]; Martinez et al. found that the sense of agency varied during a mid-air touching task, across different feedback modalities, such as visual, audio, or vibration [12]–these authors found that both auditory and haptic feedback modalities were superior to the visual-only baseline in terms of increased sense of agency; along similar lines, Limerick et al. showed that, in speech-based interfaces, the voice input modality reduces agency when compared to keyboard input [38].

However, while researchers in HCI already started exploring the sense of agency for a number of aforementioned systems, including machine-induced mouse clicks, button presses, and mid-air haptics, the understanding of the user's sense of agency in haptic systems is at its infancy–this is precisely what we advance. As such, we first cover the types of haptic devices our findings will apply to, including force-feedback devices, especially those designed for interpersonal communication of non-visual cues (proprioceptive aspects such as poses, gestures, rhythms, etc.).

2.3 Haptic devices that can generate *computer-driven touch* by actuating the user's body

The type of haptics we explore, with regards to their implications on the user's sense of agency, are strong haptic systems capable of moving a user's body, even against their own volitional force (this property of a haptic device is most often referred to as *force-feedback*). These types of devices can move the user's body, for instance, to touch a computer interface, which we refer to as *computer-driven touch*—since this type of touch is involuntary, i.e., not generated by the user but, instead, by the computer via the haptic device.

Broadly speaking, there are two types of actuators that provide enough output force to actuate human limbs, such as the force required to move a user's finger and involuntarily drive touch actions: (1) mechanical actuators (e.g., large robotic arms or exoskeletons), and (2) electrical muscle stimulation (EMS). The former is the traditional type of mechanical force feedback device, constructed by having users hold on to a handle, which is then actuated by a robotic arm or by pulley system (e.g., SPIDAR [54]). While the majority of these devices are stationary, researchers have long been exploring mechanisms to achieve ungrounded force-feedback: this is typically realized by mechanically actuated devices that provide forces by pulling the user's limbs against a mounting point on the user's body. Exoskeletons are the canonical example of a wearable ungrounded haptic device: they are often employed to actuate the user's arms [72], legs [68], or fingers [22]. Unfortunately, mechanical-based force-feedback devices are also rather impractical due to their bulky weight and size, which might explain why few such commercial devices exist despite the decades of research [40]. This led many researchers to explore alternative actuation approaches that afford smaller form-factors when compared to mechanical devices. The most promising approach to miniaturizing mechanical force feedback is precisely electrical muscle stimulation, which we cover next.

2.4 Electrical Muscle Stimulation

Electrical Muscle Stimulation (EMS) is an actuation technique with roots in rehabilitation medicine, pioneered as a means to restore lost motor functions, e.g., allow a patient to regain muscle movements even after suffering spinal cord injuries [67]. At its core, EMS uses electrical impulses to the user's muscles, delivered via electrodes attached to the skin. When these electrical impulses reach the user's muscles, they cause them to contract, which results in an involuntary movement.

A decade ago, researchers in HCI started to explor EMS as a component of interactive devices that can realize force feedback. It has been successfully used to create force-feedback in virtual reality [18, 39, 41, 44], mobile information systems [42], haptic training systems [16, 43, 58, 62, 72], and especially in interpersonal communication systems that allow users to synchronize their movements over distance (e.g., [24, 25, 58–60]–because these interactive applications of EMS are of particular relevance to our proposal, we explore them in detail next.

2.5 Interpersonal Haptic Communication

Even beyond EMS, a number of haptic devices have been developed specifically to convey one's haptic or kinetic experience to another person, with the goal of enriching communication with non-verbal aspects such as force, poses, gestures, rhythms, etc. For instance, InTouch [9] allows remote users to feel virtual sensations of a shared object through somatosensory interactions by using connected mechanical rollers. Similarly, a paired shape-shifting stick [55] allows users to feel the movements and presence of a performer by mimicking the remote user's stick movements. These haptic cues are capable of even conveying or complementing emotions, such as anger, disgust, fear, and joy [2]. Interpersonal haptic communication makes it possible to transfer not only physical skills between users [46, 63] but also improves the users' sense of presence and users' ratings of trust and togetherness [10, 34, 56]. Recently, EMS-based interpersonal communication systems are also employed for conveying non-verbal aspects, such as rhythms or force [59], joint rigidity [60], poses and presence [24], and even emotions via body gestures [25]).

2.6 Loss of agency in actuated haptic systems

Unfortunately, while researchers are excited about the prospects of haptic devices such as EMS, very little is known about their impact on the user's sense of agency. This lack of a deep understanding is where we draw inspiration for our present investigation. Specifically, we identified several instances of previous HCI studies conducted on these EMS-based interactive systems that point to some degree of the participants' loss in agency. For example, in Affordance++, participants attributed agency to the object they manipulated (e.g., a spray can that shakes) rather than to themselves [43]. Similarly, in Proprioceptive Interaction, participants often voiced not feeling in control, e.g., "it was so remarkable to see my hand moving without my intention" [42]. Moreover, Nishida et al. found in their demonstrations that the use of EMS used to speed-up a participant in a collaborative pen-drop task caused **users to have a decreased sense of agency** [58].

2.7 Attempts to preserve the user's sense of agency in haptic systems: the case of computer-driven touch

This last example led to the only known attempt to preserve the user's sense of agency in haptic actuated systems, such as those powered by EMS. Researchers found that, for a task exclusively involving touch-interactions, adjusting the timing of the preemptive assistance provided by the haptic device allows the user's to feel more **in control** [31]. In other words, delaying the **computer-driven touch timing to be closer to the user's own movement timing helped in preserving the user's sense of agency**, even when the touch was externally created by means of a haptic device, such as an EMS-based interactive device [31].

However, this prior work only considered the naive case in which the user-driven touch is aligned with the machine-driven touch [31], which we call a *joint success*. This literally assumes that the user has no choice in their touch actions. In other words, the only prior research assumes the *extremely unlikely* scenario in which the user can only touch in the same way as the machine touches (and cannot touch or do anything else, including simply not touching and remaining idle); ironically, this former investigation shows how to preserve the user's agency in a heavily-constrained scenario where the user has no real choice over their touches, which, as we saw, is a component of the sense of agency.

We argue that this is actually a rather unlikely case because it only works when we can predict the user's intention, which, as aforementioned, is typically seen as a computationally hard problem that has eluded decades of research. As such, this paper contributes an understanding of what happens to the user's sense of agency in more nuanced and complex situations where the system and the user's touch might not always be perfectly aligned. This understanding will allow researchers to effectively build better digital touch systems that can prioritize and/or trade-off between the user's sense of agency vs. the amount of haptic assistance.

3 OVERVIEW OF OUR USER STUDIES

Our experiments were designed to understand to whom users attribute a *touch* is made when their own body is actuated by a haptic device. As previously explained, we opted for electrical muscle stimulation since it presents itself as the ideal case-study as its loss of agency in EMS-driven touch is already well-known [31], while, simultaneously, EMS is seen by researchers as a very promising approach to wearable haptics.

As such, our experiments investigate the four scenarios depicted in Figure 1–allowing us to go beyond the insights from prior work [31], which only investigated the narrow situation in which the EMS and the user perform the exact same touch (no-choice). Moreover, we were interested in understanding whether this attribution of agency is modulated by the outcome of the touch action, *i.e., do we tend to attribute correct actions to ourselves, while we attribute incorrect actions to computer systems?* To investigate these key questions, we designed a novel variation of the Stroop test, a well-known cognitively demanding task [26, 50, 77], by adding electrical muscle stimulation (EMS) as our haptic device that can generate computer-driven touches; the EMS can do this because it can touch a UI faster than a participant and thus the computer-driven touch is the one generates the outcome.

3.1 Stroop test

The Stroop effect is a well-known phenomenon of cognitive interference [26, 50, 77], in which we can measure a delay in a reaction time due to a mismatch in stimuli. A popular Stroop effect example is: "touch the word red" with options "BLUE" vs. "RED". The correct answer in this example is to touch "RED", despite the fact that it is shown in a blue color. The cognitive mismatch happens between the "name of a color" (e.g., "BLUE" or "RED") and the color that the word is rendered with (i.e., the word "RED" shown in blue color instead of red color).

This cognitive interference happens robustly, even when someone is fully cognizant of the so-called Stroop effect [26, 50, 77]. Therefore, the Stroop task is extremely useful and widely used for simulating a cognitively loaded task, i.e., a task where the participant really *has to ponder their choice* before they respond with a *touch on the screen*. In this sense, the Stroop task is cognitively hard because it asks participants to choose the correct answer over two cognitively-hard-to-process items, such as our previous example: "touch the word red" with options "BLUE" vs. "RED". What often happens in this example is that participants erroneously choose the word by color, picking out "BLUE" since its color is red. There are countless variations on this well-known effect, even in non-visual modalities, such as the auditory Stroop effect [52].

3.2 Our novel variation: EMS-based Stroop test

We designed a novel variation on the Stroop test with the addition of EMS that allowed us to investigate our main research question. In our study, participants were asked to answer typical two-choice Stroop questions by touching, with either hand, a touchscreen UI. The items from which to choose were placed in either sides of the screen, therefore, to choose the left item, the participant is required to touch with their ring-finger of their left-hand, and vice versa.

Simultaneously, our EMS device actuated participants' fingers as well, therefore our EMS device can *automatically* touch for the participant—i.e., *computer-driven touch.* Moreover, it can do that either *faster* or *slower* than the participant's own reaction time; in other words, we can adjust the preemptive timing of the haptic-assistance to reveal potential effects with agency. Using this setup, we made the EMS-based haptic assistance play one of two roles: *assistive-touch* (actuated the finger to touch the correct answer) or *adversarial-touch* (actuated the finger to touch an incorrect answer). As such our unique study design allows us to simulate the situation where the computer directly assists or interferes with one's body as we are also performing a touch. Since our interest was in how participants attribute the success or failure of each touch action to themselves or to the computer, we asked participants to rate their sense of agency explicitly after each touch (as in [31]).

3.3 Apparatus

Our experimental setup is depicted in Figure 2. To assist readers in replicating our experiment, we now provide the necessary technical details and, moreover, the complete source code and EMS-stimulator design[1]. Participants sat in front of the experimental system consisting of: a touchscreen computer (Microsoft Surface Pro Model 1796, with a 60fps display). Then, in our main study, we added also two pairs of electrodes (applied on each arm, calibrated to actuate each hand's ring finger), and an EMS stimulator (bioSync [59]) connected to the computer. We also designed two 3d printed hand supports; these supports leave the participants' ring fingers free to flex and *touch* the screen so as to answer the Stroop test. Furthermore, this prevents participants muscles from fatiguing quickly.

3.4 EMS Stimulation (only in main study)

Participants were actuated using the aforementioned EMS stimulator. This study was approved by our local ethics committee (Sony Group Corporation, application 19F0010). Furthermore, during recruitment, we confirmed that no participant had any medical condition that discouraged the use of EMS.

Electrode placement: We attached two pairs of electrodes to both hands: each pair stimulated the forearm muscle responsible for flexing the ring finger (*flexor digitorum profundus).* We chose to actuate the ring finger, rather than the index finger, since previous research has confirmed that one can robustly actuate it so as to touch the screen without any parasitical motion of neighboring muscles [31, 69].

---

[1] https://lab.plopes.org/#assistedEMStouch

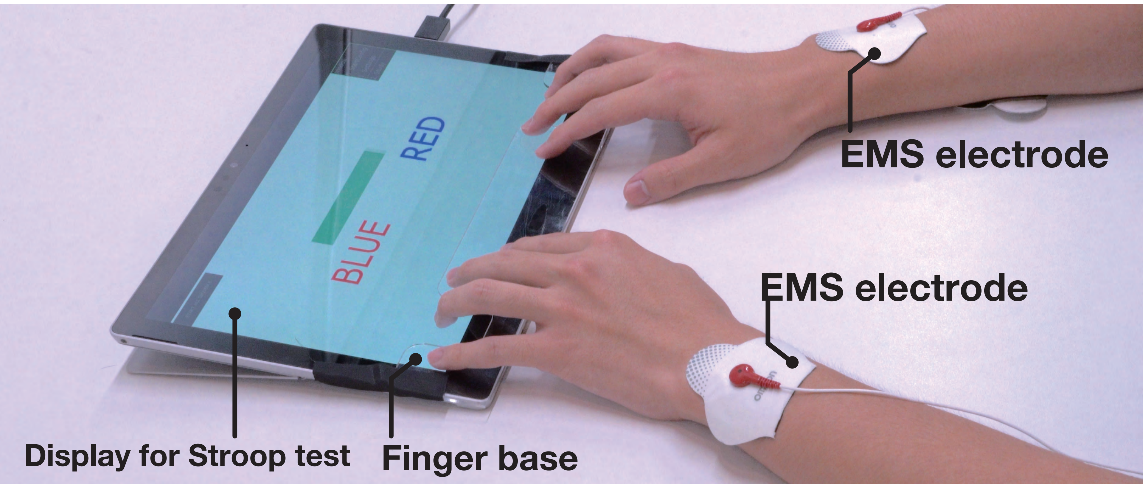

Fig. 2. The setup for our Stroop test studies. The EMS was added only for the main study.

Calibrating the EMS stimulation: We interactively adjusted the stimulation parameters to actuate both ring fingers robustly. We fixed the output of our voltage-controlled muscle stimulator at 38V [59]. Then, in order to calibrate, we adjusted the electrical impulses' pulse-width (ranging from 100-300 microseconds), the number of pulses in a stimulation (ranging from 1 to 4 pulses) and the interval between consecutive pulses (ranging from 30-100 ms, in case more than one pulse was used). We chose this since prior research suggests that short stimulations are less noticeable [41]. Prior to starting the trials, we confirmed that participants' finger was actuated via the EMS to tap the surface and that each touch was consistently recognized by the touchscreen.

3.5 Trial design

Participants performed a touch-based forced-choice task in a Stroop test setting. The design of our task, which is depicted in Figure 3 with the example of a single trial, was as follows:

(1) Fixation: The fixation cross was displayed with a randomized duration (between 1 and 4s) to keep participants attentive.

(2) Instruction for touch task: Next, participants were presented with the instruction for this trial. The choice-task was one of four possible combinations of ['RED' or 'BLUE'] and ['COLOR' and 'TEXT'], e.g. 'TOUCH RED COLOR' (touch the word colored in red), 'TOUCH BLUE TEXT' (touch the word 'blue' not matter the color in which it is printed). This instruction is shown for 300ms, which we determined via pilot testing to be sufficiently cognitively demanding.

(3) Choice & touch: Then, after being presented with the instruction, the Stroop visual stimuli appeared on the screen. The Stroop choice visual stimuli consisted of two colored words located in right and left in the screen as depicted in Figure 2. Those two words are colored contrary to the meaning of the word: for example, the word "BLUE" appeared in a red colored font, like this BLUE. Here, participants were asked to touch the correct side of the screen with the ring finger of the corresponding hand (right or left) as *fast and accurate as possible.*

In addition to the Stroop visual stimuli, we also presented participants with an on-screen time indicator to limit the maximum time available for each trial (a horizontal bar that decreased over time, depicted in Figure 2).

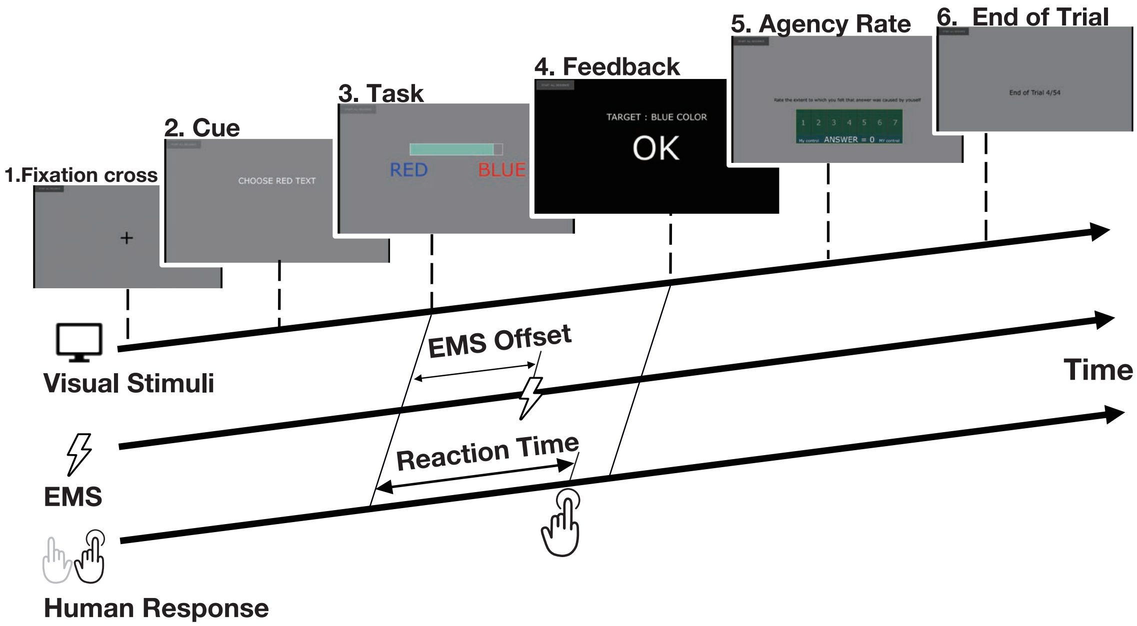

Fig. 3. Our novel variation of the Stroop test using electric muscle stimulation (EMS).

EMS-conditions: assistive-touch and adversarial-touch (main study) The EMS actuated participants' finger to answer the Stroop test by touching on behalf of the participants (involuntarily). It played two different roles in our study: **assistive-touch**, in which the EMS forced the participant's finger to touch the correct answer (success); or, **adversarial-touch**, in which the EMS forced the participant's finger to touch the incorrect answer (failure). In addition, the EMS impulse that drove the computer-driven touch was delivered with seven different timings (denoted as EMS offset): 100ms, 200ms, 275ms, 350ms, 425ms, 500ms, and 600ms, all of these are relative to the time of the visual stimulus.

(4) Outcome visual feedback: As soon as a touch was detected (by either the user's voluntary movement or EMS' involuntary action), the visual feedback showing the outcome was displayed with an "OK" or "NG" (not good) alongside this trial's instruction. While the message was displayed immediately after the first touch was detected (first touch is the one that drives the outcome), our study system also recorded any subsequent touches for our analysis.

(5) Questionnaire for sense of agency: After each touch (a Stroop question), participants were presented with a questionnaire regarding their perceived sense of agency for this trial. We follow the typical agency questionnaire, i.e., a Likert scale question with 1 = "I did not do it" and 7 = "I did it" (as in [31]).

4 PRE-STUDY: STANDARD STROOP TEST

The objective of our pre-study was to determine the typical performance participants' exhibit in an unmodified Stroop test with participants, especially: what is the average time needed to cognitively process the stimuli and touch the correct answer? We required determining this prior to advancing to our novel variation of the Stroop test because we need to know when to activate the EMS to create the computer-driven touch. Moreover, this pre-study also served as a screening process for determining which participants of our sample are eligible for the main study (more than 55% of correct answers).

4.1 Apparatus, experimental design and procedure

This study was conducted as described above, except no haptic assistance was used; in other words, participants performed a standard Stroop test using only user-driven touches. We measured the correct answer-rate and the reaction time. Before engaging in our pre-study task, participants performed a training session using congruent color and text (e.g., BLUE) for at least 10 min (simply tapping on screen to advance), to understand the task. Then, we asked participants to perform 32 Stroop trials (again, without any haptic assistance).

4.2 Participants

We recruited 18 participants (three self-identified as female, 15 as male; M= 32.8 years old, SD= 9.03) from our local institution. With their prior written consent, we transcribed their comments.

4.3 Result of pre-study

We collected 32 trials from each participant (for a total of 576 samples), with two data points each: the reaction time per touch and the correct/incorrect answer. Data was assessed for normality using the Shapiro-Wilk test ($p > .05$).

Analyzing accuracy of responses: Before analyzing between participants, we checked the accuracy of the task for each participant to exclude results around chance-level (approx. 50%), indicating the participant may not have performed the task correctly, most likely the difficulty of the Stroop test was still too high for these individuals with the given time limit. As a result, we excluded three participants whose accuracy was around chance-level (M=53.5%, SD=0.7), these did not qualify for the main study as they did not reach our eligibility criteria (more than 55% of correct answers). After excluding these three participants, the average accuracy was 77.1 ± 14.4% (of correct answers).

Analyzing average touch time: the average reaction time was 516.4 ± 54.8 milliseconds.

Analyzing touch time based on accuracy: In order to check participants' behavior according to success or failure of the task, the data separation based on the accuracy of their response was conducted (separating correct vs. incorrect trials). Averages of touch time were 516.0 ± 54.4 milliseconds for a successful response and 512.4 ± 73.3 milliseconds for failed response. Type III ANOVA analysis did not show significance in the average of reaction time between success and failure responses ($F_{1,27}$=.022, $p = .883$). This result indicates that the participant's speed did not differ based on the touch's outcome (success and failure).

Validating the added cognitive load: Knowing from the psychophysics literature that the typical reaction time involving a touch action is around 250ms [28, 65], our resulting average time of 516.4ms (SE = 14.2 ms) validated that our Stroop test successfully provided a significant cognitive load, which was a critical aspect for our main study. In addition, the analysis of correct answer rate revealed that participants often missed due to incongruency between the color and semantic information of the presented text. Based on the result of this pre-study, a participant might make a mistake once every five touches. As such, moving forward to our main study, we expected that participants would also make mistakes in the task, which will allow us to investigate our hypotheses. In this light, it once more validates the current design of our Stroop task as it successfully induced enough mistakes.

5 MAIN STUDY: EMS-BASED STROOP TEST

The objective of our main study was to investigate how participants attribute their sense of agency for the outcome of a touch, while, simultaneously, being actuated by a haptic device (EMS) that played one of two **roles**: **assistive-touch (forced success)** or **adversarial-touch** (forced failure); this investigation of the influence of both the role of the touch-assistance and timing over agency is the novel aspect of this study, which was not realized in previous work. To explore the influence of the touch timing over agency, the EMS impulse that generated the computer-driven touch was delivered with seven different timing intervals (100ms - 600ms after the Stroop task is displayed), this yields two types of experience a participant is expected to feel:

Human-computer touch-congruence: when a participant and haptic device (EMS) touch with the same finger and thus **touch the same answer**. In this pattern, there are possible sub-patterns based on our two factors: (1) outcome (correct or incorrect answer) and (2) whether computer-driven touch was faster than the user-driven touch or slower.

Human-computer touch-incongruence: when a participant and the haptic device (EMS) touch different using fingers and thus **touch different answers**. The same factors apply, however, the correct outcome to the answer in this case depends on who touched first, the user-driven touch or the computer-driven touch.

5.1 Hypotheses

Our two main hypotheses were as follows:

H1: In the event that the user and the haptic device touch in the same way (i.e., the touch outcomes are congruent), we expect that the resulting outcome (i.e., whether it is a success or a failure) will bias the attribution of the touch, even when the haptics actuates participant to touch faster than their voluntary touch; in other words, we **hypothesized the existence of an outcome bias for assistive-touches**, i.e., users would feel more agency if the outcome is favorable to them and vice-versa. As such, we expected the distribution of agency with regards to the EMS timing would follow a smooth curve similar to [31].

H2: In the event that the user and the haptic device touch in different ways (i.e., the touches are incongruent), we expected participants would be able to discriminate who initiated the touch, simply dictated by who (them or system) was faster to touch. Thus, we expected that, when compared to the congruent case (from H1), the agency scores would be separated clearly (which we expected, based on prior work, to be most visible halfway in the agency distribution curve), rather than following a smooth curve–in other words, we expected the distribution of agency scores to differ from that of [31]).

5.2 Study Procedure

To eliminate any confounding variables from the Stroop design itself, we varied all possible instructions (color or text), the position of the answer (right or left) and colors (red or blue). Furthermore, we also randomized the task sequence for all 14 conditions (seven EMS timings, two EMS roles), which in total produced 112 trials per participant.

To prevent participants' fatigue or loss of concentration, we divided our task sequence into three sessions separated by five minute breaks in between, the first and the second session had 32 trials, while the third session had 54 trials.

In addition to this, each session had an extra six trials at the start of the session. These starting trials were comprised of very fast and slow EMS offsets to allow participants to create their own consistent subjective criteria for the assessment of agency while under the EMS stimulation (fast: 100ms, slow: 600ms). The order of the task sequence was counter-balanced between participants.

5.3 Data Analysis

Data analysis pipeline: Data was assessed for normality using the Shapiro-Wilk test (p > .05). Results of the questionnaires, and part of reaction time results of the task were not normally distributed; thus, non-parametric analysis were employed for these data sets to check significance of the factors. However, after data separation based on congruence between EMS actuation and human response, the remainder sample sizes often become unequal. Therefore, a type III ANOVA was employed for main effect analysis in unequal sample size data, which is effective for unbalanced samples. In addition, data screening was conducted to exclude outliers, such as accidental touches from an extremely fast or slower than normal response (these can be typically caused by a distracted participant). The trials in which the reaction time was over ± three SD were excluded, which amounted to 0.3% from all data points.

Classifying trials as human-computer in/congruent: Our main hypotheses implies the analysis of the human-computer congruent cases vs. human-computer incongruent cases. As such, we performed a straightforward case separation into two cases based on the number of touches and the response (correct vs. incorrect). Since our Stroop task was performed with two hands, human-computer in/congruent case can be separated based on the number touches on the two sides of the screen. In Figure 4, we describe how these touch sequences allow us to separate these two cases.

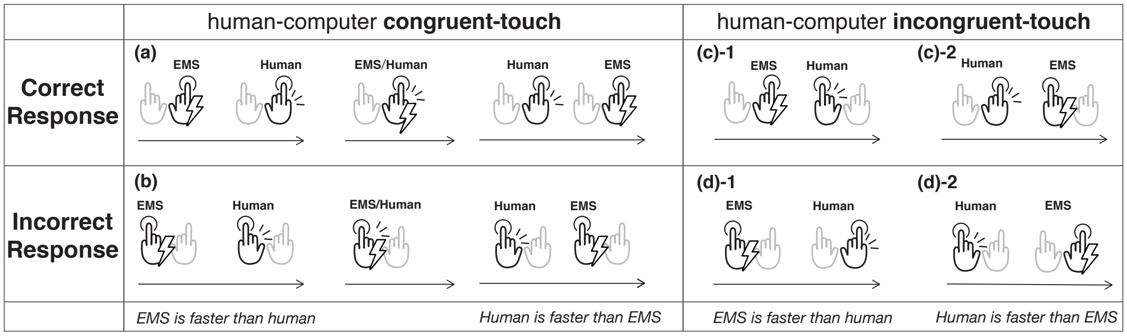

Fig. 4. Analysis cases: human-computer congruent-touch and human-computer incongruent-touch. In both cases, the response for the task can be correct or incorrect.

In the case of a human-computer **congruent-touch**, the result of user response and EMS actuation can be the same answer. In this case, touches are only detected on only the right- or left-side, regardless of whether the user or EMS is faster. The number of touches can be one or two, depending on the timing of the EMS and the user's touch, but, in either situation, this is classified as a congruent case.

In the case of human-computer **incongruent-touch**, touches are detected as a mix of right- and left-side, as EMS and the user give a different response. Therefore, regardless of the touch order, if touches are detected on both sides, it is classified as an incongruent case.

5.4 Participants

We recruited the aforementioned 15 participants that passed the eligibility criteria from the pre-study (more than 55% of correct answers). With their prior written consent, we transcribed their comments.

6 RESULTS

We collected participant responses for each trial. The total number of trials per participants was 112 (text color: red or blue; response type: text or color; correct position: right or left; EMS role: assistive or adversarial; and, EMS Offset: 7 conditions, which yields 2 x 2 x 2 x 2 x 7 = 112 trials). Across all participants we gathered 1680 trials, each containing a perceived agency score (1-7). We now analyze our hypotheses by analyzing each case: (H1) human-computer congruent-touch preserves agency and is biased towards the touch's outcome; (H2) human-computer incongruent-touch will allow participants to discriminate who delivered the touch that drove the outcome, leading to a clear distinction of agency scores (which we expected, based on prior work, to be most visible halfway in the agency distribution curve).

6.1 Human-computer congruent-touches: validating our H1

To assess our first hypothesis, we analyzed the case of human-computer congruent-touches. In this case, there are two possible outcomes: joint success (the user and EMS were both correct with assistive EMS) and joint failure (the user and EMS were both incorrect).

Perceived agency: We observed that the agency distribution across different computer-driven touch timings (how early the EMS causes the user to involuntarily touch) **is different for different outcomes**. In other words, **adversarial-touch and assistive-touch induce a different feeling of agency, even for the same EMS timing**— this is one of our key results, which is depicted in Figure 5. To confirm this, we used a two-way repeated ANOVA analysis, which revealed a significant main effect for the role of the computer-driven touch (assistive-touch vs. adversarial-touch) and the EMS offset on the agency score (EMS role: $F_{1,12}$=13.3, p =.003; EMS offset: $F_{6,79}$= 77.4, p < .001). This statistical difference confirms our first hypothesis: **participants' agency was biased towards the outcome**, i.e., for favorable outcomes (assistive), participants reported higher agency than for unfavorable outcomes (adversarial EMS). Lastly, our analysis did not find an interaction between EMS role and EMS offset ($F_{6,79}$= .92, p = .485).

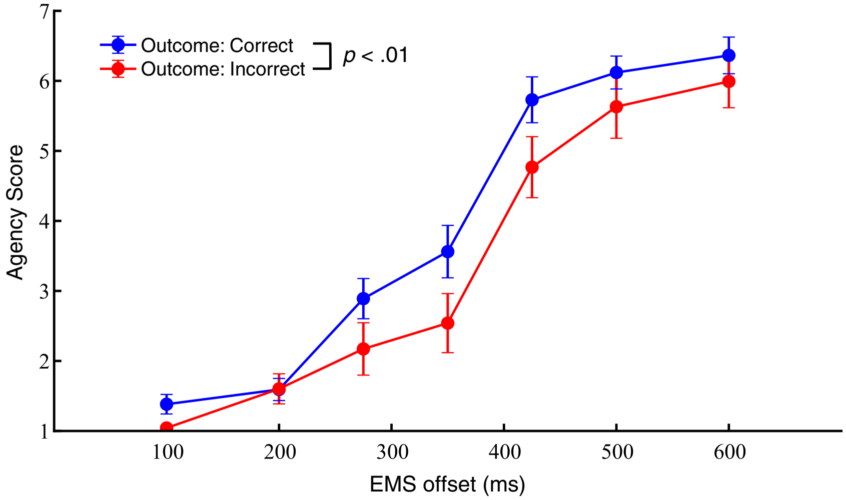

Fig. 5. Agency score with different EMS offset in the condition where computer-driven and user-driven touch were congruent (color depicts outcome, blue for positive outcome, red for negative outcome).

Furthermore, we also observed that our measured agency distributions followed a similar pattern as previously revealed by Kasahara et al. [31], as their singular case that did not involve any choice during touches. Our objective is to depict a single model that aggregates the observed agency scores across all participants. To do this, we follow the method of [31]: Per participant, we plot the logistic regression that computes the relationship between the perceived agency and the EMS offset. Then, from all these curve-fits, we computed a mean fit of $R^2 = 0.60$ (with SD=0.17, MIN=0.17, MAX=0.82) for our overall logistic model, which is depicted in Figure 6 (a) as a bold curved line with the shaded area around the curves depicting the range of its standard error. This demonstrates that the curves are in most cases very similar and relatively consistent among all users (as suggested by the low standard deviation).

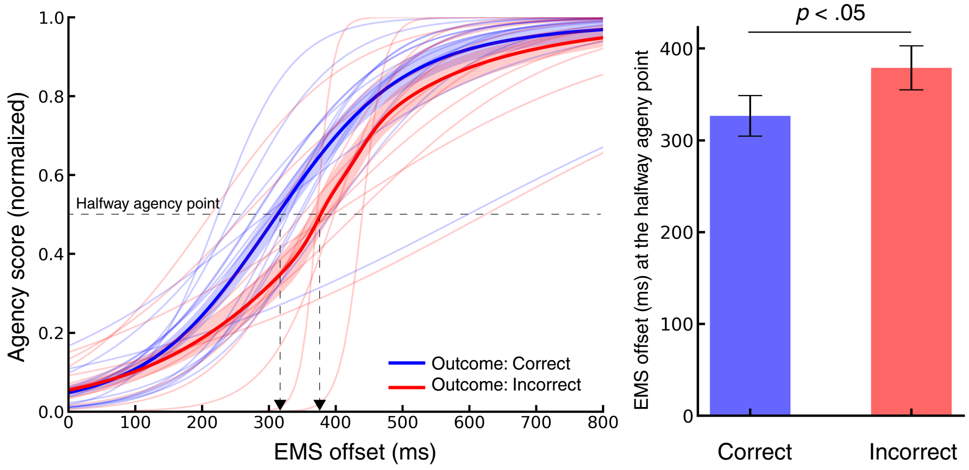

Fig. 6. (a) Result of curve fitting for each condition. (b) Comparison of estimated EMS offset, at the indicated halfway agency point (color depicts outcome, blue for positive outcome, red for negative outcome).

Impact of haptic role (assistive-touch vs. adversarial-touch) in the design of the haptic timing (EMS offset): to give readers a sense of how the haptic role (assistive-touch vs. adversarial-touch) impacts the resulting agency/touch-timing trade-off, we pick the same halfway agency point as chosen by [31], i.e., a normalized agency score of 0.5. As we can observe in Figure 6 (a), this point is reached differently depending on the haptic role (assistive-touch vs. adversarial-touch). We confirmed this via a one-sided paired T-test [2], which revealed a statistical difference between the two roles at this halfway agency point (t(13) = -3.15, p = .001.), which we depict in Figure 6 (b). As our results confirmed, the adversarial-touch role yielded a negative agency bias, and, as such, the halfway agency point is triggered by an average EMS offset of 327 ms (SE=23.8 ms). Conversely, the assistive-touch role yielded a positive agency bias, and, as such, the halfway agency point is triggered with an earlier stimulus with an average EMS offset of 379 ms (SE= 25.0 ms), meaning, when the outcomes are positive and the situation is touch-congruent, the system can accelerate the users more and, simultaneously, preserve some degree of their sense of agency—this is an implication of our findings, we will present how this affects the design of digital touch systems later. Moreover, we will depict average agency-timing trade-off curves in our resulting framework.

It is worth noting that our above insight takes into account the design of the end-to-end latency experimental apparatus (including EMS latency, touch latency, etc.), which was measured to be around 100 ms. As such, considering

---

[2] Because the sample size of data of each condition was unequal (EMS assistive-touch: 15, EMS adversarial-touch: 14), paired data were employed for this statistical analysis.

the two aforementioned average EMS offsets at the halfway agency point (327 ms and 379 ms), we can now add in the 100 ms to obtain a final reaction time of 427 ms and 479 ms. This value is below the nominal reaction time of the standard Stroop test, which we found in our Pre-study to be around 500 ms. As such, we confirm that, indeed, participants exposed to these EMS offsets can be accelerated beyond their normal reaction time while simultaneously preserving some degree of their sense of agency.

6.2 Human-computer incongruent-touch case: validating our H2

Now, we turn our attention to the extreme case, where the user-driven touch and computer-driven touch give rise to *different* answers. These competing touches generate competing outcomes, which we postulated in our second hypothesis: we expected participants would be able to discriminate who initiated the touch, simply dictated by who (user or computer) was faster to touch. To assess if indeed, as we expected, the distribution of agency scores differs from the congruent case, we conducted the same type of analysis as for the congruent-touch case, but also took into account which touch was faster (user or computer), because the fastest touch is always the one that drives the final outcome in this incongruent-touch case.

Perceived agency: We observed that the agency distribution is distinct from the congruent case and does not tend to follow the same smooth distribution (as in both our H1 or in [31]). In fact, we observed that the agency distribution is distinct when we consider both the role and the outcome (which yields four classes), as is depicted in Figure 7. We found that agency falls into two sharp and distinct regions: low-agency and high-agency (again, rather than the smooth curve from [31]), only dictated by whether the participant touched faster (higher-agency) or the computer caused the participant to tap faster (lower-agency)— this is one of our key results. In other words, when touches are at conflict between user and computer, the user's sense of agency is much easier to discriminate than in a shared touch. This insight was confirmed by a Three-way ANOVA analysis that revealed a main effect of EMS offset ($F_{6,78}$= 45.5, p < .001) and outcome ($F_{1,14}$= 16.7, p = .001) on the participants' perceived agency. Moreover, we did not find a main effect of the EMS role (assistive vs. adversarial) on the sense of agency ($F_{1,7}$=.719, p =.424)). Taken together, these two significant effects confirm our second hypothesis. Moving forward, we will visually illustrate, in our final design implications, this clear separation of the sense of agency for incongruent-touch cases as a sharp agency curve (almost like a square wave step function, from 0 to 1, i.e., from very-low to very-high agency).

7 DISCUSSION

We now discuss how our results can both validate existing research and help shape the current theories of how haptic devices, with a particular emphasis on EMS, interface with the user's sense of agency.

7.1 Outcome bias

The most intriguing and exciting of our findings is that the outcome bias has been observed even when the users' bodies were haptically actuated to induce a touch that they did not generate. Here, we ground our outcome bias finding in existing research.

Outcome bias (often dubbed as self-serving bias, as it serves one's own interests) has been reported in various experiments both in cognitive science [20] as well as in behavioral science [75]. Outcome bias is a well-known human tendency that individuals ascribe success to their own abilities and efforts, but ascribe failure to external factors [8]. The origins of outcome bias have been often pointed to the sense of agency [3, 71, 79]. For instance, correlation between

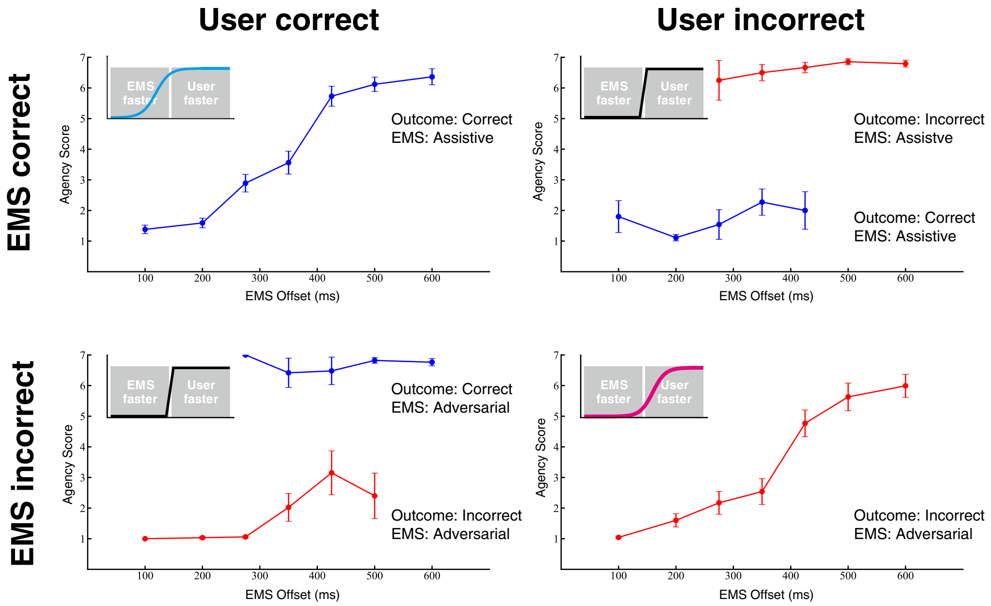

Fig. 7. Distribution of agency for incongruent-touch cases, separated into four sub-cases based on both the haptic role and the touch outcome (color depicts the outcome, blue for positive outcome, red for negative outcome).

agency measurements and positive vs. negative outcomes have been shown in several aspects such as emotional or monetary gain [71, 79].

While previous findings in sense of agency and outcome bias focused on the relationship between an action and its outcome, our findings shed light on a novel direction between voluntary touches and haptic-induced touches, which is of particular relevance to interactive systems at large, but especially to digital touch systems.

7.2 Postdictive attribution in human-computer joint actions

One theory postulates that outcome bias also happens at a higher cognitive level, on a reflective level; in other words, when we look back at our action (in retrospect), we will more likely favor attributing it to us if the outcome was positive [45, 73]. Such contribution of a retrospective process to conscious experience is often called *postdiction*, which has been shown to be an important component in the subjective experience of sequential events such as visual motion perception [15, 64] and even causality judgment [11].

7.3 Clear discrimination in incongruent-touches

Our results suggest that participants felt a clear distinction of agency for incongruent touches. So we ask: what cues do users tend to rely on to understand if the system is forcing them to touch?

Haptic cue#1 the EMS tingling sensation: One of the possible cues that participants might use to make judgments of their sense of agency during a computer-driven touch is the so called "tingling sensation" that EMS induces in the user's skin–a tactile cue. This haptic cue allows a user of a haptic system to reason/discriminate between their voluntary touch and computer-induced touch. The first implication this has for HCI research is: the tingling sensation is a limitation of EMS and needs to be addressed, but this problem is non-trivial and has escaped a solution in both HCI as well as in medical rehabilitation, the field where EMS originated from decades ago. Moreover, the tingling sensation is present in all cases of our study, but in some cases participants did indeed feel agency, even when they were still able to feel this haptic cue. As such, the cue alone is not what drives the distinction between "I did it" vs. "the UI did it", but likely provides one more piece of information available to users. In fact, one expects that this cue is more noticeable when it strikes the arm that did not touch (e.g., in the cases where user and system touched differently). Conversely, in the case where this cue is felt at the arm the user is intending to touch with, it is downplayed by the user's own sensory attenuation [6] –this is a well-known effect in which the sensory consequences of an user's actions are perceived less intensely than sensory stimuli that are not caused and thus not predicted. Precisely this type of sensory attenuation has also been measured, using fMRI, for users subjected to EMS movements [37].

Haptic cue#2 the sensation of the computer-induced touch itself: Another possible cue that users might use to reason about their sense of agency is the unexpected somatosensory feedback induced by the EMS as it contracts their muscles to touch with their finger (this is a proprioceptive cue, not a tactile cue as the previous one). Again, due to sensory attenuation [6, 37] we expect this cue to be more easily discernible for incongruent situations, i.e., participants would feel that both hands were moving, but their intention should have led only to one contraction; allowing participants to reason the cause of the touch.

7.4 Study limitations

As with any experimental design, our study has limitations that we urge readers to be aware of, prior to generalizing any of our insights. The first one is that any haptics study of this nature needs to choose a haptic-device; we chose electrical muscle stimulation since the loss of agency during EMS-driven touch is well-known from prior art, such as from [31, 42], just to cite a few. While we do believe these findings might generalize well beyond EMS, future work is needed to apply our novel study design to more and more haptic actuators.

Finally, note that while we provide one possible interpretation of our results, we argue for exploring more interpretations by designing upcoming experiments that can narrow down on the exact causes of the observed effects. For instance, the perception of who finalized the touch action can also be driving the agency perception in retrospect, which could also explain how different EMS timings causes different feelings of agency.

8 SYNTHESIS OF OUR FINDINGS: AGENCY-ASSISTANCE TRADE-OFF MATRIX

From our findings, we synthesized a matrix that generalizes the use of touch assistance beyond the simple case covered by prior art [31]. This resulted in what we call the *agency-assistance trade-off matrix*, which effectively illustrates the design implication for haptic systems that proactively actuate the user.

Our agency-assistance trade-off matrix, depicted in Figure 8 consists of four quadrants, guided by two dimensions: whether the user-driven touch is correct or incorrect, and whether the computer-driven touch is correct or incorrect. More interestingly, in each quadrant we depict an agency curve that demonstrates how likely it is that the prospective UI designer can preserve the user's agency by adjusting the timing of the computer-driven touch stimulus. To simplify the reading of these curves, we depict each by using a simple pictograph of either a smooth curve or a sharp curve. A smooth curve indicates that we found that it is possible to preserve the user's agency to some degree, while a sharp curve indicates that the haptic assistance will create a trade-off with agency. In the most immediate future, we believe these curves might directly empower researchers in this area who are building haptic interfaces with assistive-touch.

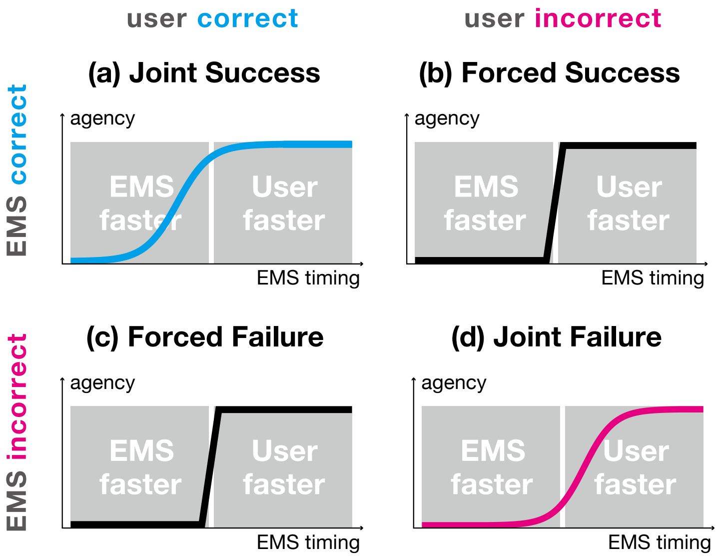

Fig. 8. Agency-assistance trade-off matrix: Four quadrants, each depicting the general trend we observed regarding the trade-off between agency and haptic assistance. Our matrix is guided by two dimensions: whether the user-driven touch is correct or incorrect, and whether the computer-driven touch is correct or incorrect.

Furthermore, we expect that, as more research follows and refines our findings and recommendations, these curves might also prove beneficial as aids for prospective designers in this area.

To better illustrate our recommendations for digital touch systems, we describe the details of each quadrant. Furthermore, we also demonstrate examples of how a prospective researcher or designer might apply this matrix for digital touch or, generally speaking, interactive haptic systems in which either the UI or a remote user assists the local user via computer-driven touches.

8.1 Quadrant (a): Joint Success

Our first quadrant depicts the case of a joint success (Figure 8 - a), depicting a congruent situation in which both the user-driven touch and the computer-driven touch result in a positive (correct) outcome for the user. This is naturally a best-case scenario as it is possible to preserve some level of sense of agency even when EMS-driven touch is faster than the user's own touch. The result is that the haptic system accelerates the user's touch, but note that the user would respond correctly anyway; in other words, the benefit is an assistive touch speed-up. This situation aligns with prior literature on simple touch interactions accelerated by haptics [31]. However, one must also denote the extreme assumption for the HCI designer, because this quadrant is unlikely: it assumes one can both predict the user's intention and with sufficient time to preemptively touch.

Typical application examples of this quadrant include relatively simple reaction tasks such as haptic assistance to catch a falling object between two users, such as the pen-drop shown in Figure 9(a) (from [31]) or touch-assistance that lets users press the shutter button of a camera to take a picture of a high-speed moving object Figure 9(b) (from [31]). Moreover, these scenarios are not limited to computer-to-user assistance, but lend themselves well to inter-personal communication scenarios too. For instance, a skilled video-game player can provide touch-assistance so that the novice

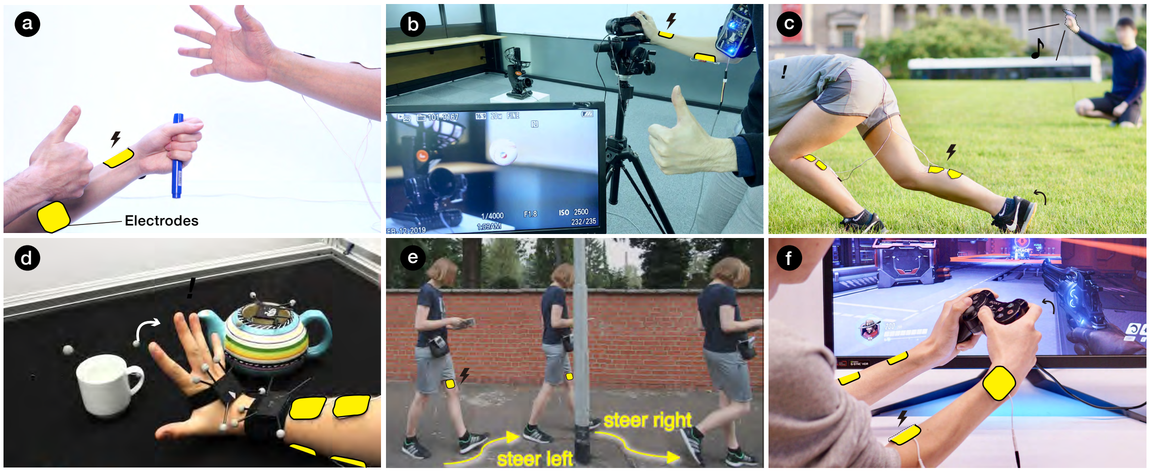

Fig. 9. Exemplary interactive applications from the HCI community where one might apply our findings: (a) a two-user situation in which they collaborate to catch a falling object (pen drop) [58], (b) accelerating a user for high-speed photography [57] and (c) speeding-up reaction time for sports. As such, (a) - (c) are exemplary cases of Joint Success. (d) EMS haptics actuate the user's hand to prevent touching a hot object [43], (e) EMS actuates the user' legs to direct their walking, including avoiding hitting a lamp post [62]. As such, (d) and (e) are example case where forced success will benefit users. Lastly, (f) Game with EMS assistance from other agents (remote user or a UI). This depicts a case that should be designed with agency priority where both joint success or joint failure will be expected.

user can perform touches faster in time-demanding games [32], such as the fast-paced video game depicted in Figure 9 (f).

Similarly, this touch-assistance might lend itself well to many other motor skill transfers from skilled user to novices [70]. In these examples the interactive system can clearly predict the user's intention from context and a plethora of additional sensors (e.g., EMG to detect the falling pen and a ball-toss sensor to detect the ball launch). We recommend that this type of preemptive touch is used in situations where user's touch intention is relatively easy to predict at a high degree of confidence; as such, the result is that the agency curve will follow our smooth distribution, meaning it is possible to still accelerate users to perform these touches or even more general movements with haptic assistance while preserving some sense of agency. We also recommend that this is the best case scenario, in which designers can opt for the most extreme accelerations, making it suitable for these types of impressive physical augmentations that depict faster-than-human touch ability.

8.2 Quadrant (b): Forced Success

Our second quadrant depicts the case of a forced success, which we depict in Figure 8 (b). Here, despite the computer-driven touch is incongruent to that of the user, the touch results in a positive outcome; in contrast, the user-driven touch would have resulted in an negative outcome. In other words, this is a corrective type of touch-assistance that dramatically helps the user obtain the right outcome. While this provides positive outcomes, it comes as a trade-off to the user's sense of agency. We depict this via the sharp agency trade-off curve, suggesting users will be sensitive to the touch-assistance and decrease their sense of agency.

As our studies revealed for this quadrant, both the outcome and agencysimply depend on whether the user or computer was faster to touch. If computer-driven touch is faster than the user-driven touch, the outcome of the action will be positive (correct) with a faster involuntary movement by the EMS, but the user is not likely to feel agency. While this pattern eventually diminishes the user's sense of agency, it is still important to consider this case as it can assist users. This is especially beneficial in safety situations or guidance/training environments. In the case of critical situations (e.g., avoiding accidents), the touch-assistance should be applied regardless of the user's touch and negative impact on agency. We can find exemplary EMS-based haptic applications from HCI literature that explore this quadrant, such as the *Affordance++* system that uses EMS to actuate the user's arm to prevent touching hot objects that might harm the user [43]. In this example, the EMS actuation is not always aligned with the user's action, but it is beneficial to prioritize the assistance as it brings users to safety. Similarly, for the case of guidance/training systems, one could envision a variation on *Pedestrian Cruise Control*, a system that uses EMS to control the user's walking direction so as to avoid colliding with incoming obstacles [62], that would allow, for instance, guiding users into choosing a better path (e.g., a shorter path or even a safer path) and thus creating incongruent situations where the EMS overrides the user's walking direction.

8.3 Quadrant (c): Forced Failure

Our third quadrant depicts the case of a forced failure, which is depicted in Figure 8(c). This is the situation that prospective designers want to most likely avoid. In this case, the computer-driven touch results in an incongruent and incorrect outcome (e.g., this could be due to tracking errors, prediction errors, false-positives, or over-fitting in gesture recognizers, etc.), but the user-driven touch results in the correct response. As such, the prospective designer should use all the available means to prevent this case. For instance, most tracking systems and predictive UIs report a level of confidence with their prediction. We strongly recommend that, if this prediction is low (i.e., the system is unlikely to be making a correct guess), the haptic assistance should be dismissed entirely as it will force only negative results and most likely decrease the sense of agency.

8.4 Quadrant (d): Joint Failure

Our fourth and last quadrant depicts the case of a joint failure, as shown in Figure 8(d). It is an congruent situation in which the computer-driven touch and the user-driven touch result in an incorrect outcome. This is a case that may occur when the system can estimate users' intention with high accuracy, but does not know what could be a positive outcome (e.g., task is too computationally complex to be solved in run-time, etc.). While this initially seems like a dead-end for designers, we would like to show how our results provide insights and even opportunities for this extreme case.

First, the prospective designer might refrain from resolving this situation by claiming that "the result of this touch is failure anyway, so why bother?" This is a fallacy. As our results reveal, if the touch-assistance accelerates the user's touch towards an imminent failure, this will not only enforce the early negative result, but also further exacerbate the loss of the sense of agency due to the negative outcome bias we observed in our studies (see Figure 5). In general, this is likely to be avoided.

While accelerating users' touch for incorrect answers is not in itself very beneficial from a practical point of view, this approach can be an intriguing and novel design opportunity in that one can create interfaces where users do not blame themselves too much when they fail a task. In other words, we can construct interfaces that sees the imminent failure and *takes the blame for it*, which might be especially relevant for preserving the user's motivation in arduous training tasks or even inter-personal communication systems for multiple users leveraging haptic-assistance via computer-driven touch.

8.5 Designing haptic interfaces mindfully regarding the agency vs. assistance trade-off

By taking insights from these our different quadrants into account, our agency-assistance trade-off matrix assists prospective designers in improving their digital touch systems, especially applicable to those based on EMS. Here, we describe design implications using two trade-off types: (1) prioritizing the sense of agency during assisted-touch or (2) trading agency for touch-assistance that ensures positive outcomes.

If a prospective designer wants to **prioritize the sense of agency** of a user who experiences computer-driven touch, they should design their interactive system in such a way that promotes (a) joint success and/or (d) joint failure cases. Technically speaking, the target interface should make use of reliable and robust ways to estimate the user's intentions to ensure that the computer-driven touch and the user-driven touch are aligned. For instance, designers should make use of the confidence intervals provided by the recognizers in real-time to regulate the amount of touch-assistance, following the agency curves we depicted in these two quadrants. As we have demonstrated, these cases will enable situations where the user feels that their touch is haptically accelerated and still feels agency.

On the other hand, if the prospective designer wants to **prioritize the touch-assistance for positive outcomes**, the interactive system should be designed in such a way that promotes (a) joint success and (b) forced success. Since EMS will create computer-driven touches with correct outcomes, we can expect either speeding up the touch that drives the correct response or correcting the user's touch into the right outcome. None of these will guarantee that agency is preserved but there are some extra considerations designers should keep in mind. Especially in the case of interfaces that deal with critical or emergency scenarios (health, etc.), the system should prevent injury to the user. As such, **touch-assistance with positive outcome is prioritized** over the sense of agency. Even if this kind of touch-assistance removes the user's agency entirely, the outcome is tremendously beneficial to the user. As such, if the interactive system can predict risky scenarios (e.g., such as touching the hot cup in [43] or hitting the lamp post while walking in [62]), the designers should actuate the haptic-assistance regardless of the role (forced success or joint success). Again, we believe that this is not only relevant for the design of single-user applications but also for multi-user applications, such as interpersonal communication systems that use haptic actuation, for instance, in remote communication between users for telepresence and/or skill-transfer over the network [1, 33, 70].

9 CONCLUSION

We believe that this paper empowers HCI researchers to consider not only *touch* as a depiction of haptic qualities (e.g., texture) but also consider the challenge of *assisted-touch*, i.e., a touch that is driven by the computer interface via force feedback.

As such, we advanced our understanding of digital touch systems by contributing to the study and design of what happens when digital touch systems can *make their user touch the UI* involuntarily. While this type of force-feedback is known to enhance the interpersonal-communication by empowering remote users to share non-verbal aspects such as rhythm, poses, etc., it also requires forcing the user's body to move against their intention–this computer-driven touch, unfortunately, causes users to lose their sense-of-agency. While researchers have proposed that delaying the timing of the computer-driven touch closer to the user's own voluntary touch preserves some sense of agency, this was only considered for the simplest case, in which the users have no choice as to what they will touch. We argued that this is an unlikely case, as it assumes we can perfectly predict the user's own touches. But, what about all the remainder situations: when the haptics forces the user into an outcome they did not intend, or when the haptics assists the user in an outcome they would not achieve alone?

We unveiled, via our experiments, what happens in these novel situations. We found out that participant's attribution of agency was biased (positively and negatively) by the outcomes, when the computer-driven touch and the user-driven touch are aligned. On the other hand, when the computer-driven touch created an outcome not intended by a participant, the attribution of the agency appeared easier to distinguish. Finally, from these study findings, we synthesized a framework that enables researchers/practitioners of digital-touch systems to prioritize/trade-off between haptic-assistance and sense-of-agency. As of now, our findings originate from using EMS as the case study for this loss of agency in haptic systems. Moving forward, we would expect future researchers to apply and extend our novel study to other force-feedback devices (e.g., magnetic actuation of the finger, mechanical force-feedback joysticks, exoskeletons, etc.), ultimately contributing to a larger understanding that might generalize better.

Finally, we believe that, as we design new types of haptic systems with the capability to perform actions in behalf of users, we start to encounter all these cases of complex/shared agencies. We believe our study systematically explored many of these cases, in particular the situations in which the computer's and user's intentions are in conflict. While these are not yet commonplace, that is precisely our job as researchers to anticipate the future and design it mindfully of the user's agency.

10 ACKNOWLEDGMENTS

Firstly, we would like to thank the TOCHI reviewers and editors for their valuable feedback. Secondly, we would like to thank our colleague Jas Brooks for assisting us in proof-reading this manuscript. This work was supported by Grant-in-Aid for JSPS Research Fellow (JP16J03777) and in part by NSF grants 2047189 and 2024923. This work was also supported by JST Moonshot R&D Program (Grant Number JPMJMS2013). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of any funding agencies.

REFERENCES

[1] E J Avila Mireles, J Zenzeri, V Squeri, P Morasso, and D De Santis. 2017. Skill Learning and Skill Transfer Mediated by Cooperative Haptic Interaction. *IEEE Trans. Neural Syst. Rehabil. Eng.* 25, 7 (July 2017), 832–843.

[2] Jeremy N. Bailenson, Nick Yee Ph.D., Scott Brave Ph.D., Dan Merget, and David Koslow. 2007. Virtual Interpersonal Touch: Expressing and Recognizing Emotions Through Haptic Devices. *Human-Computer Interaction* 22, 3 (2007), 325–353. https://doi.org/10.1080/07370020701493509 arXiv:https://www.tandfonline.com/doi/pdf/10.1080/07370020701493509

[3] Zeynep Barlas, William E. Hockley, and Sukhvinder S. Obhi. 2018. Effects of free choice and outcome valence on the sense of agency: evidence from measures of intentional binding and feelings of control. *Experimental Brain Research* 236, 1 (Jan. 2018), 129–139. https://doi.org/10.1007/s00221-017-5112-3

[4] Bruno Berberian, Jean-Christophe Sarrazin, Patrick Le Blaye, and Patrick Haggard. 2012. Automation Technology and Sense of Control: A Window on Human Agency. *PLOS ONE* 7, 3 (March 2012), e34075. https://doi.org/10.1371/journal.pone.0034075

[5] Joanna Bergstrom-Lehtovirta, David Coyle, Jarrod Knibbe, and Kasper HornbÃęk. 2018. I Really did That: Sense of Agency with Touchpad, Keyboard, and On-skin Interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. ACM Press, Montreal QC, Canada, 1–8. https://doi.org/10.1145/3173574.3173952

[6] S J Blakemore, D Wolpert, and C Frith. 2000. Why can't you tickle yourself? *Neuroreport* 11, 11 (aug 2000), R11–6. http://www.ncbi.nlm.nih.gov/pubmed/10943682

[7] M. Botvinick and J. Cohen. 1998. Rubber hands 'feel' touch that eyes see. *Nature* 391, 6669 (Feb. 1998), 756. https://doi.org/10.1038/35784

[8] Gifford W. Bradley. 1978. Self-serving biases in the attribution process: A reexamination of the fact or fiction question. *Journal of Personality and Social Psychology* 36, 1 (1978), 56–71. https://doi.org/10.1037/0022-3514.36.1.56

[9] Scott Brave and Andrew Dahley. 1997. InTouch: A Medium for Haptic Interpersonal Communication. In *CHI '97 Extended Abstracts on Human Factors in Computing Systems* (Atlanta, Georgia) *(CHI EA '97)*. Association for Computing Machinery, New York, NY, USA, 363–364. https:

//doi.org/10.1145/1120212.1120435

[10] Scott Brave, Clifford Nass, and Erenee Sirinian. 2001. Force-Feedback in computer-mediated communication. In *Universal Access In HCI: Towards an Information Society for All, Proceedings of HCI International '2001 (the 9th International Conference on Human-Computer Interaction), New Orleans, USA, August 5-10, 2001, Volume 3*, Constantine Stephanidis (Ed.). Lawrence Erlbaum, 145–149.

[11] Hoon Choi and Brian J. Scholl. 2006. Perceiving causality after the fact: postdiction in the temporal dynamics of causal perception. *Perception* 35, 3 (2006), 385–399. https://doi.org/10.1068/p5462

[12] Patricia Ivette Cornelio Martinez, Silvana De Pirro, Chi Thanh Vi, and Sriram Subramanian. 2017. Agency in Mid-air Interfaces. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 2426–2439. https://doi.org/10.1145/3025453.3025457

[13] David Coyle, James Moore, Per Ola Kristensson, Paul Fletcher, and Alan Blackwell. 2012. I did that!: measuring users' experience of agency in their own actions. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*. ACM Press, Austin, Texas, USA, 2025. https://doi.org/10.1145/2207676.2208350

[14] Nicole David, Stefan Skoruppa, Alessandro Gulberti, Johannes Schultz, and Andreas K. Engel. 2016. The Sense of Agency Is More Sensitive to Manipulations of Outcome than Movement-Related Feedback Irrespective of Sensory Modality. *PLOS ONE* 11, 8 (Aug. 2016), e0161156. https://doi.org/10.1371/journal.pone.0161156

[15] D. M. Eagleman and T. J. Sejnowski. 2000. Motion integration and postdiction in visual awareness. *Science (New York, N.Y.)* 287, 5460 (March 2000), 2036–2038. https://doi.org/10.1126/science.287.5460.2036

[16] Ayaka Ebisu, Satoshi Hashizume, Kenta Suzuki, Akira Ishii, Mose Sakashita, and Yoichi Ochiai. 2016. Stimulated Percussions: Techniques for Controlling Human As Percussive Musical Instrument by Using Electrical Muscle Stimulation. In *SIGGRAPH ASIA 2016 Posters* (Macau) *(SA '16)*. ACM, New York, NY, USA, Article 37, 2 pages. https://doi.org/10.1145/3005274.3005324

[17] Kai Engbert, Andreas Wohlschlager, and Patrick Haggard. 2008. Who is causing what? The sense of agency is relational and efferent-triggered. *Cognition* 107, 2 (May 2008), 693–704. https://doi.org/10.1016/j.cognition.2007.07.021

[18] Farzam Farbiz, Zhou Hao Yu, Corey Manders, and Waqas Ahmad. 2007. An Electrical Muscle Stimulation Haptic Feedback for Mixed Reality Tennis Game. In *ACM SIGGRAPH 2007 Posters* (San Diego, California) *(SIGGRAPH '07)*. ACM, New York, NY, USA, Article 140. https://doi.org/10.1145/1280720.1280873

[19] Umer Farooq and Jonathan Grudin. 2016. Human-computer integration. *interactions* 23, 6 (2016), 26–32.

[20] Leon Festinger. 1957. *A theory of cognitive dissonance*. Stanford University Press.

[21] C. D. Frith, S. J. Blakemore, and D. M. Wolpert. 2000. Abnormalities in the awareness and control of action. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 355, 1404 (Dec. 2000), 1771–1788. https://doi.org/10.1098/rstb.2000.0734

[22] Xiaochi Gu, Yifei Zhang, Weize Sun, Yuanzhe Bian, Dao Zhou, and Per Ola Kristensson. 2016. Dexmo: An Inexpensive and Lightweight Mechanical Exoskeleton for Motion Capture and Force Feedback in VR. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. ACM, New York, NY, USA, 1991–1995. https://doi.org/10.1145/2858036.2858487

[23] Patrick Haggard, Sam Clark, and Jeri Kalogeras. 2002. Voluntary action and conscious awareness. *Nature Neuroscience* 5, 4 (April 2002), 382–385. https://doi.org/10.1038/nn827

[24] Shin Hanagata and Yasuaki Kakehi. 2018. Paralogue: A Remote Conversation System Using a Hand Avatar Which Postures Are Controlled with Electrical Muscle Stimulation. In *Proceedings of the 9th Augmented Human International Conference* (Seoul, Republic of Korea) *(AH '18)*. Association for Computing Machinery, New York, NY, USA, Article 35, 3 pages. https://doi.org/10.1145/3174910.3174951

[25] Mariam Hassib, Max Pfeiffer, Stefan Schneegass, Michael Rohs, and Florian Alt. 2017. *Emotion Actuator: Embodied Emotional Feedback through Electroencephalography and Electrical Muscle Stimulation*. Association for Computing Machinery, New York, NY, USA, 6133–6146. https://doi.org/10.1145/3025453.3025953

[26] Andrew Heathcote, Stephen J. Popiel, and D. J.K. Mewhort. 1991. Analysis of response time distributions: an example using the stroop task. *Psychological Bulletin* 109, 2 (1991), 340–347. https://doi.org/10.1037/0033-2909.109.2.340

[27] Pilwon Heo, Gwang Min Gu, Soo-jin Lee, Kyehan Rhee, and Jung Kim. 2012. Current hand exoskeleton technologies for rehabilitation and assistive engineering. *International Journal of Precision Engineering and Manufacturing* 13, 5 (May 2012), 807–824. https://doi.org/10.1007/s12541-012-0107-2

[28] R Hyman. 1953. Stimulus information as a determinant of reaction time. *J. Exp. Psychol.* 45, 3 (March 1953), 188–196.

[29] Marc Jeannerod. 2003. The mechanism of self-recognition in humans. *Behavioural Brain Research* 142, 1-2 (June 2003), 1–15. https://doi.org/10.1016/S0166-4328(02)00384-4

[30] C. Jeunet, L. Albert, F. Argelaguet, and A. Lecuyer. 2018. "Do You Feel in Control?": Towards Novel Approaches to Characterise, Manipulate and Measure the Sense of Agency in Virtual Environments. *IEEE Transactions on Visualization and Computer Graphics* 24, 4 (April 2018), 1486–1495. https://doi.org/10.1109/TVCG.2018.2794598

[31] Shunichi Kasahara, Jun Nishida, and Pedro Lopes. 2019. Preemptive Action: Accelerating Human Reaction using Electrical Muscle Stimulation Without Compromising Agency. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*. ACM Press, Glasgow, Scotland Uk, 1–15. https://doi.org/10.1145/3290605.3300873

[32] Shunichi Kasahara, Kazuma Takada, Jun Nishida, Kazuhisa Shibata, Shinsuke Shimojo, and Pedro Lopes. 2021. Preserving Agency During Electrical Muscle Stimulation Training Speeds up Reaction Time Directly After Removing EMS. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–9.

[33] T Kurogi, M Nakayama, K Sato, S Kamuro, C L Fernando, M Furukawa, K Minamizawa, and S Tachi. 2013. Haptic transmission system to recognize differences in surface textures of objects for telexistence. In *2013 IEEE Virtual Reality (VR)*. 137–138.

[34] Daniel Leithinger, Sean Follmer, Alex Olwal, and Hiroshi Ishii. 2014. Physical Telepresence: Shape Capture and Display for Embodied, Computer-Mediated Remote Collaboration. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology* (Honolulu, Hawaii, USA) *(UIST '14)*. Association for Computing Machinery, New York, NY, USA, 461–470. https://doi.org/10.1145/2642918.2647377

[35] BENJAMIN LIBET, CURTIS A GLEASON, and ELWOOD W WRIGHT. [n.d.]. TIME OF CONSCIOUS INTENTION TO ACT IN RELATION TO ONSET OF CEREBRAL ACTIVITY (READINESS-POTENTIAL). ([n. d.]), 20.

[36] Jakub Limanowski and Felix Blankenburg. 2016. That's not quite me: limb ownership encoding in the brain. *Social Cognitive and Affective Neuroscience* 11, 7 (July 2016), 1130–1140. https://doi.org/10.1093/scan/nsv079

[37] Jakub Limanowski, Pedro Lopes, Janis Keck, Patrick Baudisch, Karl Friston, and Felix Blankenburg. 2020. Action-dependent processing of touch in the human parietal operculum and posterior insula. *Cerebral Cortex* 30, 2 (2020), 607–617.

[38] Hannah Limerick, James W. Moore, and David Coyle. 2015. Empirical Evidence for a Diminished Sense of Agency in Speech Interfaces. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 3967–3970. https://doi.org/10.1145/2702123.2702379

[39] Pedro Lopes and Patrick Baudisch. 2013. Muscle-propelled Force Feedback: Bringing Force Feedback to Mobile Devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Paris, France) *(CHI '13)*. ACM, New York, NY, USA, 2577–2580. https://doi.org/10.1145/2470654.2481355

[40] P. Lopes and P. Baudisch. 2017. Immense Power in a Tiny Package: Wearables Based on Electrical Muscle Stimulation. *IEEE Pervasive Computing* 16, 03 (jul 2017), 12–16. https://doi.org/10.1109/MPRV.2017.2940953

[41] Pedro Lopes, Alexandra Ion, and Patrick Baudisch. 2015. Impacto: Simulating Physical Impact by Combining Tactile Stimulation with Electrical Muscle Stimulation. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software; Technology* (Charlotte, NC, USA) *(UIST '15)*. ACM, New York, NY, USA, 11–19. https://doi.org/10.1145/2807442.2807443

[42] Pedro Lopes, Alexandra Ion, Willi Mueller, Daniel Hoffmann, Patrik Jonell, and Patrick Baudisch. 2015. Proprioceptive Interaction. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. ACM, New York, NY, USA, 939–948. https://doi.org/10.1145/2702123.2702461

[43] Pedro Lopes, Patrik Jonell, and Patrick Baudisch. 2015. Affordance++: Allowing Objects to Communicate Dynamic Use. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. ACM, New York, NY, USA, 2515–2524. https://doi.org/10.1145/2702123.2702128

[44] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. ACM, New York, NY, USA, 1471–1482. https://doi.org/10.1145/3025453.3025600

[45] Takaki Maeda, Motoichiro Kato, Taro Muramatsu, Satoru Iwashita, Masaru Mimura, and Haruo Kashima. 2012. Aberrant sense of agency in patients with schizophrenia: forward and backward over-attribution of temporal causality during intentional action. *Psychiatry Research* 198, 1 (June 2012), 1–6. https://doi.org/10.1016/j.psychres.2011.10.021

[46] Azumi Maekawa, Shota Takahashi, MHD Yamen Saraiji, Sohei Wakisaka, Hiroyasu Iwata, and Masahiko Inami. 2019. Naviarm: Augmenting the Learning of Motor Skills Using a Backpack-Type Robotic Arm System. In *Proceedings of the 10th Augmented Human International Conference 2019* (Reims, France) *(AH2019)*. Association for Computing Machinery, New York, NY, USA, Article 38, 8 pages. https://doi.org/10.1145/3311823.3311849

[47] Masao Matsuhashi and Mark Hallett. 2008. The timing of the conscious intention to move. *The European journal of neuroscience* 28, 11 (Dec. 2008), 2344–2351. https://doi.org/10.1111/j.1460-9568.2008.06525.x

[48] Alan McCall, Maurizio Fanchini, and Aaron J Coutts. 2017. Prediction: the modern-day sport-science and sports-medicine âĂIJquest for the holy grailâĂİ. *International journal of sports physiology and performance* 12, 5 (2017), 704–706.

[49] John McEneaney. 2013. Agency Effects in Human-Computer Interaction. *International Journal of Human-Computer Interaction* 29 (Sept. 2013), 798–813. https://doi.org/10.1080/10447318.2013.777826

[50] D. J.K. Mewhort, J. G. Braun, and Andrew Heathcote. 1992. Response Time Distributions and the Stroop Task: A Test of the Cohen, Dunbar, and McClelland (1990) Model. *Journal of Experimental Psychology: Human Perception and Performance* 18, 3 (1992), 872–882. https://doi.org/10.1037/0096-1523.18.3.872

[51] Christopher A. Miller and Raja Parasuraman. 2007. Designing for Flexible Interaction Between Humans and Automation: Delegation Interfaces for Supervisory Control. *Human Factors* 49, 1 (Feb. 2007), 57–75. https://doi.org/10.1518/001872007779598037

[52] A L Morgan and J F Brandt. 1989. An auditory Stroop effect for pitch, loudness, and time. *Brain Lang.* 36, 4 (May 1989), 592–603.

[53] Florian Floyd Mueller, Pedro Lopes, Paul Strohmeier, Wendy Ju, Caitlyn Seim, Martin Weigel, Suranga Nanayakkara, Marianna Obrist, Zhuying Li, Joseph Delfa, et al. 2020. Next Steps for Human-Computer Integration. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–15.

[54] Jun Murayama, Laroussi Bougrila, Yanlinluo Katsuhito Akahane, Shoichi Hasegawa, Béat Hirsbrunner, and Makoto Sato. 2004. SPIDAR G&G: A two-handed haptic interface for bimanual VR interaction. In *Proceedings of EuroHaptics 2004*.

[55] Ken Nakagaki, Chikara Inamura, Pasquale Totaro, Thariq Shihipar, Chantine Akikyama, Yin Shuang, and Hiroshi Ishii. 2015. Linked-Stick: Conveying a Physical Experience Using a Shape-Shifting Stick. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human

Factors in Computing Systems (Seoul, Republic of Korea) *(CHI EA '15)*. Association for Computing Machinery, New York, NY, USA, 1609–1614. https://doi.org/10.1145/2702613.2732712

[56] Hideyuki Nakanishi, Kazuaki Tanaka, and Yuya Wada. 2014. Remote Handshaking: Touch Enhances Video-Mediated Social Telepresence. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI '14)*. Association for Computing Machinery, New York, NY, USA, 2143–2152. https://doi.org/10.1145/2556288.2557169

[57] Jun Nishida, Shunichi Kasahara, and Pedro Lopes. 2019. Demonstrating Preemptive Reaction: Accelerating Human Reaction Using Electrical Muscle Stimulation Without Compromising Agency. In *ACM SIGGRAPH 2019 Emerging Technologies (SIGGRAPH '19)*. ACM, New York, NY, USA, 10:1–10:2. https://doi.org/10.1145/3305367.3327997

[58] Jun Nishida, Shunichi Kasahara, and Kenji Suzuki. 2017. Wired Muscle: Generating Faster Kinesthetic Reaction by Inter-personally Connecting Muscles. In *ACM SIGGRAPH 2017 Emerging Technologies* (Los Angeles, California) *(SIGGRAPH '17)*. ACM, New York, NY, USA, Article 26, 2 pages. https://doi.org/10.1145/3084822.3084844

[59] Jun Nishida and Kenji Suzuki. 2017. *BioSync: A Paired Wearable Device for Blending Kinesthetic Experience.* Association for Computing Machinery, New York, NY, USA, 3316–3327. https://doi.org/10.1145/3025453.3025829

[60] J. Nishida, K. Yagi, M. Hassan, and K. Suzuki. 2019. Wearable Kinesthetic I/O Device for Sharing Wrist Joint Stiffness. In *2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. 3306–3310. https://doi.org/10.1109/EMBC.2019.8857538

[61] Jay A. Olson, Mathieu Landry, KrystÃĺle Appourchaux, and Amir Raz. 2016. Simulated thought insertion: Influencing the sense of agency using deception and magic. *Consciousness and Cognition* 43 (July 2016), 11–26. https://doi.org/10.1016/j.concog.2016.04.010

[62] Max Pfeiffer, Tim Dünte, Stefan Schneegass, Florian Alt, and Michael Rohs. 2015. Cruise Control for Pedestrians: Controlling Walking Direction Using Electrical Muscle Stimulation. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. ACM, New York, NY, USA, 2505–2514. https://doi.org/10.1145/2702123.2702190

[63] MHD Yamen Saraiji, Tomoya Sasaki, Reo Matsumura, Kouta Minamizawa, and Masahiko Inami. 2018. Fusion: Full Body Surrogacy for Collaborative Communication. In *ACM SIGGRAPH 2018 Emerging Technologies* (Vancouver, British Columbia, Canada) *(SIGGRAPH '18)*. Association for Computing Machinery, New York, NY, USA, Article 7, 2 pages. https://doi.org/10.1145/3214907.3214912

[64] Shinsuke Shimojo. 2014. Postdiction: its implications on visual awareness, hindsight, and sense of agency. *Frontiers in Psychology* 5 (2014). https://doi.org/10.3389/fpsyg.2014.00196

[65] Irwin W Silverman. 2010. Simple reaction time: it is not what it used to be. *Am. J. Psychol.* 123, 1 (2010), 39–50.

[66] Chun Siong Soon, Anna Hanxi He, Stefan Bode, and John-Dylan Haynes. 2013. Predicting free choices for abstract intentions. *Proceedings of the National Academy of Sciences* 110, 15 (2013), 6217–6222.

[67] P. Strojnik, A. Kralj, and I. Ursic. 1979. Programmed Six-Channel Electrical Stimulator for Complex Stimulation of Leg Muscles During Walking. *IEEE Transactions on Biomedical Engineering* BME-26, 2 (Feb 1979), 112–116. https://doi.org/10.1109/TBME.1979.326520

[68] Kenta Suzuki, Gouji Mito, Hiroaki Kawamoto, Yasuhisa Hasegawa, and Yoshiyuki Sankai. 2007. Intention-based walking support for paraplegia patients with Robot Suit HAL. *Advanced Robotics* 21, 12 (2007), 1441–1469. https://doi.org/10.1163/156855307781746061 arXiv:https://www.tandfonline.com/doi/pdf/10.1163/156855307781746061

[69] Akifumi Takahashi, Jas Brooks, Hiroyuki Kajimoto, and Pedro Lopes. 2021. Increasing Electrical Muscle Stimulation's Dexterity by Means of Back of the Hand Actuation. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 216, 12 pages. https://doi.org/10.1145/3411764.3445761

[70] Nobuhiro Takahashi, Hayato Takahashi, and Hideki Koike. 2019. Soft Exoskeleton Glove Enabling Force Feedback for Human-Like Finger Posture Control with 20 Degrees of Freedom. In *2019 IEEE World Haptics Conference (WHC)*. IEEE, Tokyo, Japan, 217–222. https://doi.org/10.1109/WHC.2019.8816142

[71] Keisuke Takahata, Hidehiko Takahashi, Takaki Maeda, Satoshi Umeda, Tetsuya Suhara, Masaru Mimura, and Motoichiro Kato. 2012. ItâĂŹs Not My Fault: Postdictive Modulation of Intentional Binding by Monetary Gains and Losses. *PloS one* 7 (Dec. 2012), e53421. https://doi.org/10.1371/journal.pone.0053421

[72] Emi Tamaki, Takashi Miyaki, and Jun Rekimoto. 2011. PossessedHand: Techniques for Controlling Human Hands Using Electrical Muscles Stimuli. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. ACM, New York, NY, USA, 543–552. https://doi.org/10.1145/1978942.1979018

[73] Daniel M. Wegner. 2003. The mind's best trick: how we experience conscious will. *Trends in Cognitive Sciences* 7, 2 (Feb. 2003), 65–69.

[74] Sebastien Weibel, Patrick Eric Poncelet, Yvonne Delevoye-Turrell, Antonio Capobianco, Andre Dufour, Renaud Brochard, Laurent Ott, and Anne Giersch. 2015. Feeling of control of an action after supra and subliminal haptic distortions. *Consciousness and Cognition* 35 (Sept. 2015), 16–29. https://doi.org/10.1016/j.concog.2015.04.011

[75] Bernard Weiner. 2006. *Social motivation, justice, and the moral emotions: An attributional approach.* Lawrence Erlbaum Associates Publishers, Mahwah, NJ, US.

[76] Andrew Wold, Jakub Limanowski, Henrik Walter, and Felix Blankenburg. 2014. Proprioceptive drift in the rubber hand illusion is intensified following 1 Hz TMS of the left EBA. *Frontiers in Human Neuroscience* 8 (2014). https://doi.org/10.3389/fnhum.2014.00390

[77] Motonori Yamaguchi, Emma L. Clarke, and Danny L. Egan. 2018. Is Your Color My Color? Dividing the Labor of the Stroop Task Between Co-actors. *Frontiers in Psychology* 9, August (2018), 1–11. https://doi.org/10.3389/fpsyg.2018.01407

[78] Yasuhisa Hasegawa, Yasuyuki Mikami, Kosuke Watanabe, and Yoshiyuki Sankai. 2008. Five-fingered assistive hand with mechanical compliance of human finger. In *2008 IEEE International Conference on Robotics and Automation*. 718–724. https://doi.org/10.1109/ROBOT.2008.4543290

[79] Michiko Yoshie and Patrick Haggard. 2013. Negative Emotional Outcomes Attenuate Sense of Agency over Voluntary Actions. *Current Biology* 23, 20 (Oct. 2013), 2028–2032. https://doi.org/10.1016/j.cub.2013.08.034