Double-Sided Tactile Interactions for Grasping in Virtual Reality

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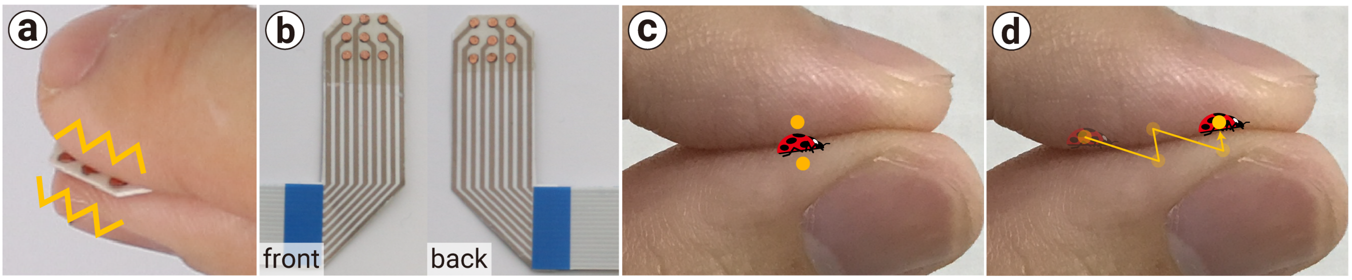

Figure 1: We propose (a) a double-sided electrotactile device with a thin and flexible form factor. (b) The device comprises two overlapping electrode arrays that leverage the high tactile acuity of fingerpads to open a rich space of single-sided and double-sided tactile interactions for pinching in virtual reality. Double-sided interactions enable (c) simultaneous double-sided stimulation to create the sensation of holding a virtual object in-between fingers, and (d) spatiotemporal double-sided stimulation to represent the movement of a virtual object between fingers.

ABSTRACT

For grasping, tactile stimuli to multiple fingertips are crucial for realistic shape rendering and precise manipulation. Pinching is particularly important in virtual reality since it is frequently used to grasp virtual objects. However, the interaction space of tactile feedback around pinching is underexplored due to a lack of means to provide co-located but different stimulation to finger pads. We propose a double-sided electrotactile device with a thin and flexible form factor to fit within pinched fingerpads, comprising two overlapping 3 × 3 electrode arrays. Using this new tactile interface, we define a new concept of *double-sided tactile interactions* with three feedback modes: (1) *single-sided stimulation*, (2) *simultaneous double-sided stimulation*, and (3) *spatiotemporal double-sided stimulation*. Through two user studies, we (1) demonstrate that participants can accurately discriminate between single-sided and double-sided stimulation and find a qualitative difference in tactile sensation; and (2) confirm the occurrence of apparent tactile motion between fingers and present optimal parameters for continuous or discrete movements. Based on these findings, we demonstrate five VR applications to exemplify how double-sided tactile interactions can produce spatiotemporal movement of a virtual object between fingers and enrich touch feedback for UI operation.

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CCS CONCEPTS

• **Human-centered computing → Haptic devices**.

KEYWORDS

Haptics; tactile display; electrotactile stimulation; double-sided; virtual reality; skin.

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1 INTRODUCTION

Researchers have explored many ways to virtually reproduce touch interactions between hands and objects using haptics interfaces [6]. For grasping, tactile stimuli to multiple fingertips are crucial for realistic shape rendering [4] and precise manipulation [12, 30]. Among grasping gestures, pinching is particularly important in virtual reality (VR) since it is considered the most used hand gesture in hand-tracking VR HMDs when grasping objects [42, 43]. Therefore, researchers have proposed various tactile devices that stimulate two fingers (index, thumb) in pinching, often using vibrotactile feedback [3, 29, 30, 48] or skin-stretching feedback [9, 26, 32, 41]. Due to the mechanical actuators used, these devices tend to be rather large, obstructing the finger pinch and limiting the feedback to a single stimulus across a fingerpad.

Inspired by prior work on electrotactile interfaces [33, 34], we propose a double-sided electrotactile device with a thin and flexible form factor to comfortably fit within pinched fingerpads (Figure 1a). The device comprises two overlapping 3 × 3 electrode arrays

(Figure 1b) to independently render the same or different stimuli on each fingerpad, leveraging fingerpads' high spatial acuity in tactile perception. To our knowledge, it is the thinnest and most flexible double-sided tactile stimulation device. We use this new tactile interface to define a new concept of *double-sided tactile interactions* at pinched fingers with three modes of feedback: (1) conventional *single-sided stimulation* on the front *or* back side; (2) *simultaneous double-sided stimulation*, in which the device stimulates both fingers simultaneously; and (3) *spatiotemporal double-sided stimulation*, where the device stimulates both fingers' electrodes in sequence. Due to the generality of pinching in many grasping events in VR, these interactions open a new space for tactile interactions for grasping in VR. For instance, double-sided interactions with high spatial and temporal acuity offer new opportunities for creating the sensation of grabbing a virtual object in-between the finger-pinch (Figure 1c) and a virtual object moving between the two fingerpads (Figure 1d).

We experimentally confirm two previously unexplored fundamentals of double-sided electrotactile interactions that need to be met for these interactions: (1) The user can successfully distinguish between single-sided and simultaneous double-sided stimulation. Results from our first user study demonstrate that participants could distinguish between stimuli to the index finger only, thumb only, and both fingers with an average accuracy of 97.8%. (2) Spatiotemporal double-sided stimulation can elicit a continuous moving sensation between two fingers. Our second study confirmed the occurrence of apparent tactile motion [13] between fingers and clarified the optimal parameters to elicit continuous or discrete spatiotemporal movements between fingers.

Based on these findings, we demonstrate five VR example applications to exemplify how double-sided tactile interactions can produce spatiotemporal movement of a virtual object between fingers, such as (1) a moving ladybug and (2) rotating planets, and enrich touch feedback for UI operation, such as (3) slider manipulation, (4) selection in a pie menu, and (5) pop-up effects. We conclude by discussing further use cases of our double-sided interface that involve skin sites other than fingerpads.

2 RELATED WORK

Our work builds on the intersection of three research areas: electrotactile stimulation, haptic devices for grasping and pinching, and apparent tactile motion.

2.1 Electrotactile Stimulation

Electrotactile stimulation has attracted attention due to the feasibility of tactile stimulation in a small form factor [27]. Electrotactile devices elicit tactile sensation by applying the electrical current to the skin via electrodes in contact with the skin and directly activating sensory nerves [18]. The current flows through a subdermal area from anode electrodes (connected to high voltage) to cathode electrodes (connected to the ground). High-speed switching of each electrode between high voltage or ground allows for spatiotemporal feedback or stimulation at a wide range of frequencies [18]. Very recent work achieved tactile stimuli of high spatial resolution (76 dots/cm^2) with a low voltage of 13V [31]. Electrotactile electrodes can be made thin and flexible by putting conductive traces on various substrates, including coated paper [11, 22], temporary tattoo paper [52], and silicone [53]. Due to its compactness, electrotactile stimulation has been applied in various applications, such as for feel-through haptic feedback in mixed reality [52], touchscreens [17, 25], and artificial tactile feedback for a myoelectric prosthesis [8].

Electrotactile stimulation can elicit various tactile sensations. Kajimoto et al. proposed "tactile primary color approach" to selectively stimulate three mechanoreceptors related to different tactile sensations: Merkel cell disks (SA1) for pressure, Meissner corpuscles (RA) for low-frequency vibration, and Pacinian corpuscles (PC) for high-frequency vibration [20]. The current distribution of electrodes determined which mechanoreceptor was stimulated [20]. Especially, anodic stimulation (the target electrode is connected to high voltage and other electrodes to the ground) stimulated RA, while cathodic stimulation (the target electrode is connected to the ground and other electrodes to high voltage) stimulated SA1 and PC [20]. Anodic stimulation elicited an "acute vibratory" sensation, while cathodic stimulation elicited a "vague pressure" sensation [21]. Other than tactile feedback, electrotactile stimulation has also been applied to provide pseudo-force feedback [33, 34] and thermal sensation [39].

2.2 Haptic Devices for Grasping and Pinching

Grasping is a common touch interaction in everyday contexts. Therefore, a number of devices have been proposed to stimulate fingers and a palm during grasping gestures in VR, such as shape-changing mechanical displays [10, 45, 50, 54], brake mechanisms [3, 4, 7, 55], on-demand proxies [28], and pneumatically inflated pouches [47]. Among the grasping gestures, pinching is especially frequently used in VR for picking virtual objects or manipulating a UI with the thumb and index finger. Mechanical haptic devices for pinching can be divided into two main form factors. The first consists of mounting a small motor on each of the two fingers to provide vibrotactile feedback [29, 37, 48] or to deform fingerpads [9, 32, 41]. The second type comprises handheld devices incorporating brake mechanisms [5, 44], vibration motors [30, 46], or spinning disks [26].

Some electrotactile devices stimulated multiple fingers simultaneously. Nakayama et al. stimulated the pinched fingers with a 10 mm thick rigid double-sided electrotactile stimulator to provide pseudo-force feedback in vertical [33] and horizontal [34] directions. Kato et al. and Hummel et al. attached electrotactile devices to multiple fingers [12, 22]. Yao et al. presented a full-hand electrotactile interface [53].

Extending these prior works with a thin and flexible double-sided interface, we add a new perspective of *double-sided tactile interactions* to haptic devices for grasping and pinching. While some past works have used similar device setups, none of them showed double-sided tactile interactions. Kato et al. used double-sided conductive patterns to provide both tactile and frictional force feedback to a single finger by generating electrical stimuli on the finger side and electrostatic force on the other side [22], thus cannot be used for double-sided tactile stimulation. Nakayama et al. created one

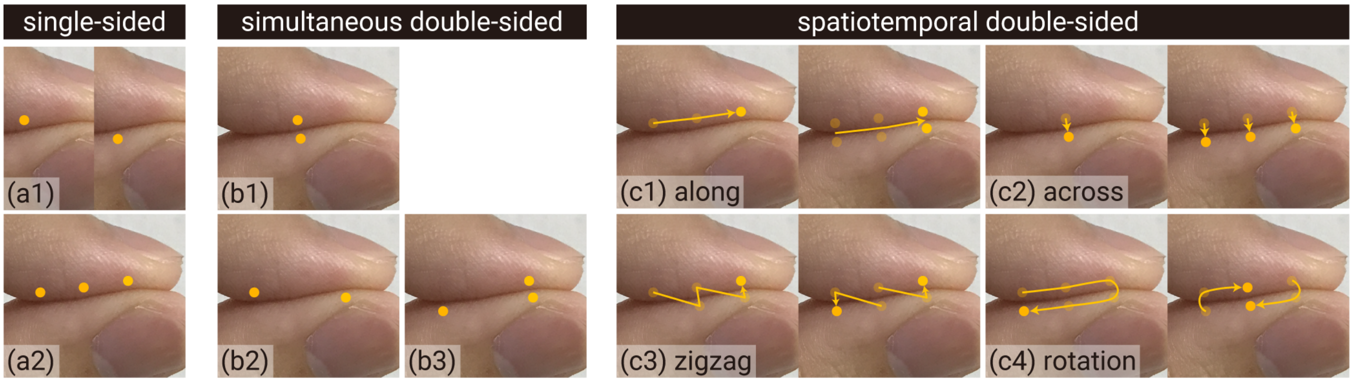

Figure 2: The conceptual space of double-sided tactile interactions is subdivided into three main feedback modes: (a) single-sided stimulation, (b) simultaneous double-sided stimulation, and (c) spatiotemporal double-sided stimulation.

integrated pseudo-force sensation in a single direction by synchronizing electrodes on opposing sides in a specific time-synchronized pattern [33, 34]. In contrast, we provide double-sided and co-located stimuli that can be selectively stimulated independently as either side or both. Withana et al. presented an ultra-thin finger-worn electrotactile interface for feel-through haptics, but investigated only single-sided stimulation [52].

2.3 Apparent Tactile Motion

Apparent tactile motion (ATM) is a frequently studied tactile illusions in spatiotemporal tactile feedback [13]. When two tactile stimuli are generated at close proximity on the skin with a slight time shift, the user feels an illusory stimulus between the two [13]. ATM has been demonstrated to occur on the torso [13, 49], finger [16], and between two hands [35, 36, 56].

Inter-stimulus onset asynchrony (SOA, the time interval between the two successive stimuli) significantly affects the perception of spatiotemporal tactile patterns [13]. Depending on an SOA value, the user's perception of spatiotemporal feedback is divided into three sensations: simultaneous, discrete, and continuous [13, 49]. In simultaneous sensation, the user feels two stimuli are rendered at the same time. In discrete sensation, the user feels two independent stimuli with a time gap. In continuous sensation, the user feels as if a stimulus smoothly moves from one point to another. We investigate ATM for double-sided electrotactile interactions and experimentally identify the SOA values for smooth movement across both sides of the device.

3 DOUBLE-SIDED TACTILE INTERACTIONS

In this section we explore the conceptual interaction space opened by double-sided tactile interactions. We classified double-sided tactile interactions into three main feedback modes: single-sided, simultaneous double-sided, and spatiotemporal double-sided stimulation. Figure 2 outlines several examples for each mode. For visual clarity, we show only simple point or line patterns here. Many more variations, including 2D and 2.5D patterns, can be presented depending on the spatial resolution of the stimulation interface used.

Single-sided stimulation stimulates either the index or thumb. In its simplest form, the user can selectively feel one stimulus point (Figure 2a1). The user can also feel a broader spatial distribution (Figure 2a2) by rendering multiple stimulus points, creating a 1D or 2D pattern. This mode corresponds to a classical fingerpad worn electrotactile display [22, 52], but with the benefit of being able to selectively render on either of both fingerpads.

Simultaneous double-sided stimulation stimulates both fingers simultaneously. The interface can simultaneously stimulate two co-located points on the front and back sides (Figure 2b1), creating the sensation of a cue located in-between the two fingers. The interface can also stimulate two points that are not co-located (Figure 2b2) or combine single-sided with double-sided stimuli (Figure 2b3).

Spatiotemporal double-sided stimulation moves single-sided or double-sided stimuli spatiotemporally, creating the sensation of a cue moving between fingers. In the **along** pattern, the user feels a single-sided stimulus or double-sided stimuli moving along fingerpads (Figure 2c1). In the **across** pattern, the user feels single-sided stimuli moving from one finger to the other (Figure 2c2). This pattern can elicit continuously or discretely moving sensations depending on timing parameters [13], as we will experimentally confirm below. The **zigzag** pattern is an extension of the across pattern and makes the stimuli move between the two fingers alternately (Figure 2c3). Finally, in the **rotation** pattern, the user feels stimuli that rotating along or across the fingerpads (Figure 2c4). Multiple patterns can be combined, e.g., simultaneously presenting the across pattern between two points and the along pattern going through other points.

In this paper, we will investigate these interactions using electrotactile stimulation. However, we note that these are not linked to a specific device and are generalized to other tactile rendering technologies that offer localized stimuli on both the front and back sides.

4 IMPLEMENTATION

To achieve these double-sided tactile interactions with a thin and flexible form factor, we developed a double-sided electrotactile stimulation device. This device comprised (1) flexible electrode arrays and (2) a control circuit.

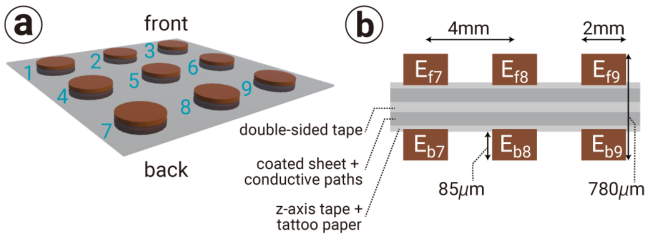

Figure 3: Our finger-worn interface has (a) a 3 × 3 electrode array on both the front and back sides. (b) These arrays with the same layout are stacked using double-sided adhesive tape.

4.1 Flexible Electrode Arrays

The two electrode arrays for each side were first made separately with a matching electrode layout and then combined using double-sided adhesive tape (3M 467MP) to create the double-sided interface as depicted in Figure 3b. The electrodes and conductive paths were printed with silver nanoparticle-based ink (Mitsubishi NBSIJ-MU01) on coated paper (Mitsubishi NB-RC-3GR120) using a commodity inkjet printer (EPSON WorkForce WF-2010W). The final finger-worn device is thin and bendable [23, 24]. To ensure close contact between the skin and electrodes, we attached z-axis conductive tape (3M) over the electrodes, cut copper tape with a commodity craft cutter (Brother ScanNCut) to fit the circular shape of a printed electrode, and put two layers of copper tape on top of z-tape. Finally, we insulated the conductive paths other than electrodes by putting a laser-cut adhesive sheet on the index side and a laser-cut temporary tattoo paper on the thumb side. Each electrode array was taped to a flexible flat cable via the z-axis tape and connected to the control circuit. The overall thickness of the interface is 780 µm.

Each side of the device features 3 × 3 electrodes of 2 mm diameter arranged with 4 mm center-to-center spacing (Figure 3b). This spacing follows prior electrotactile interfaces [11, 52] and is comparable with the two-point discrimination threshold of fingertips in electrotactile stimulation [21]. This paper will refer to the front electrodes as E_{f1}-E_{f9} and the back electrode as E_{b1}-E_{b9}, as shown in Figure 3a. This electrode layout is suitable for selectively stimulating Meissner corpuscles with anodic pulses [19]. Our implementation stacks the flexible electrode arrays on one finger, to ensure that double-sided stimuli are co-located. Future implementations could alternatively use two separate electrotactile interfaces on different fingers, allowing stimuli to be delivered even when the fingerpads are separated; however, this would require highly accurate detection of the respective finger positions to ensure that stimuli are co-located on both sides when the fingerpads are touching.

4.2 Control Circuit

Replicating the same circuit as [52], we made a custom current control circuit capable of generating an electric current in the range of 0–2.7 mA, controllable with 200 discrete steps. We used anodic pulses with a maximum pulse width of 200 µs to generate a localized [21] and pain-free [18] tactile sensation. The frequency range was 1 - 200 Hz, covering the effective frequency range to stimulate Meissner corpuscles [19]. The current was applied to the desired electrode using multiplexers (Supertex HV513). The current-controlled circuit applied current in a safe range regardless of the fingers' skin impedance to assure safety [18, 52]. The circuit constantly measured the current flowing through the skin via a unity-gain voltage differential amplifier (Texas Instruments INA149). As there is a conductive path from the index finger to the thumb through the hand, we had to set only one electrode to high voltage and the others to the ground at a time to get a localized stimulus point. Our control circuit is capable of switching each electrode *ON* and *OFF* at a high speed at 5 kHz and we use time division multiplexing at this speed to simulate simultaneous stimulus points, similar to single-sided stimulation [21, 40]. We implemented two control user interfaces running on a Windows PC (Alienware m17 R5) using Python and Unity. The control circuit and PC can be connected via Bluetooth or a USB cable (serial port).

5 EVALUATION

To validate our interface for double-sided tactile interactions, we conducted two user studies. All our studies were approved by the University Ethical Review Board (No. 22-11-1).

Both studies used our double-sided interface setup on a table. Participants placed their dominant arm on an armrest and held the double-sided interface between the thumb and index finger of the same hand. The index finger touched the front side, and the thumb touched the back side. The interface was placed centrally so that the center electrode of each side of the interface was close to the center of the fingerpad.

We recruited ten participants (aged 23 to 42; six identified as male, four as female; all right-handed) and they participated in both studies. A 5-minute break was taken between the two studies. The entire procedure took 1 hour.

5.1 Study 1: Discrimination between Single-Sided and Double-Sided Stimulation

Our first study aimed to investigate whether users can distinguish between three types of stimuli: index finger-only, thumb-only, and for both fingers simultaneously. This factor is the most fundamental in double-sided tactile interactions and has not yet been examined in prior work. This validation is particularly important given the high variability of electrotactile sensation between stimulated positions or persons [18, 27].

5.1.1 Conditions. The study investigated three types of *stimulated fingers*: index-only, thumb-only, and both fingers. We opted for comparing them for two different *pulse frequencies*: 30 Hz and 50 Hz. 30 Hz is a frequency value in the range where Meissner corpuscles are most sensitive to touch [19]. 50 Hz was also chosen as a frequency value that participants could discriminate from 30 Hz [19]. We chose center electrodes (E_{f5} for the index and E_{b5} for the thumb) as the anode electrodes to provide the stimulus to each finger. For both frequencies, we used anodic pulses with a pulse width of 200 µs of constant amplitude.

5.1.2 Calibration. Before trials, we calibrated pulse amplitudes for both electrodes in both frequencies. For each electrode, the amplitude was gradually increased from a minimum value of 0.5 mA and set to a value at which the participant perceived a clear, pain-free stimulus. The amplitudes for both fingers were adjusted so that the intensity felt in each finger was approximately the same when each finger was alternately stimulated. This procedure was conducted for each frequency. For 30 Hz, the average amplitude values were 1.72 mA (SD = 0.18) for E_{f5} and 1.87 mA (SD = 0.17) for E_{b5}. For 50 Hz, the average amplitude values were 1.72 mA (SD = 0.14) for E_{f5} and 1.77 mA (SD = 0.13) for E_{b5}.

5.1.3 Trial Design and Procedure. In each trial, the participant was presented with two 500 ms long stimuli, separated by a 1s long pause. Each of the two stimuli was selected from three different stimulation types: index only, thumb only, both fingers. After each trial, we asked the participants "Were the same fingers stimulated in the two patterns?", with 2 alternative forced choices (AFC), "yes" or "no" as the answer. The answer should be 'yes' if the participant felt the two stimuli were of the same stimulation type (e.g., 'index only' and 'index only') and 'no' if they were of different types (e.g., 'index only' and 'both fingers'). We explained to participants in advance how to answer the question with these concrete examples. The trial was repeated when requested until the participant had formed a clear opinion. Each participant performed 36 trials (2 frequencies × 6 combinations between the three stimulation types × 3 repetitions) in a randomized order. The order of the two patterns within each combination was also randomized. After having completed all the trials, we asked the participant for qualitative feedback.

5.1.4 Results and Discussion. The overall average accuracy was 97.8% (SE = 1.6), suggesting participants could accurately discriminate between single-sided and double-sided stimulation. All participants were confident about this discrimination task, stating "*it was quite easy*" (P9) or "*if only index, or only thumb, or both fingers are stimulated, they feel very different*" (P2). Some participants requested repeats in the first trials due to unfamiliarity with the procedure, but once they got used to it, they rarely asked for a repeat.

Eight participants found a qualitative difference in sensation between single-sided and double-sided stimulation. Six participants described double-sided stimulation created a sensation of holding something in the middle of two fingers rather than on one side: *"[in single-sided stimulation] it feels like it's on that side [= index] or that side [= thumb]. (...) [in double-sided stimulation] there is something middle vibrating"* (P2) or *"for the single-sided, it felt like that someone is pressing something on my finger. (...) for double-sided, I felt that I'm holding something. (...) it's similar like [an] insect is trying to fly and then you hold"* (P9). More concretely, two participants expressed they felt a point-like stimulus shape from double-sided stimulation: *"It [= double-sided] would feel like a point. (...) for single-sided, it wasn't a point. (...) it could be a line or some area"* (P7) or *"it's [= double-sided] like a small round object. (...) one-sided [stimulation] feels more like tickling"* (P6).

Two participants commented double-sided stimulation provided a stronger tactile sensation: *"[double-sided stimulation is] more intensive"* (P8) or *"if vibrated from both sides, they felt stronger than the individual ones. They kind of added up or they combined"* (P10). This finding is promising because double-sided electrotactile stimulation might provide a stronger sensation than single-sided one without exceeding a pain threshold, one of the largest challenges in controlling intensity in electrotactile stimulation [18]. Interestingly, P3 even mentioned the *naturalness* of double-sided stimulation: *"[in double-sided stimulation] when I'm holding on to this and both sides are vibrating, it feels like it can be something in real life that is vibrating. (...) It's more natural. (...) [in single-sided stimulation] it's more artificial because I guess I would expect the other one to have that vibration"*.

The accuracy was equally high regardless of the pulse frequency. The average accuracy was 97.2 % (SE = 2.8) for 30 Hz and 98.3 % (SE = 0.8) for 50 Hz. Contrasting with findings from past work [19], only four participants could find a difference in tactile sensation between 30 Hz and 50 Hz. They felt 50 Hz was a smoother continuous vibration, stating *"the first one [= 30 Hz] was a bit more spiky, (...) sharp, pointy. And, the second one [= 50 Hz] was a bit smoother"* (P10) or *"the first one [= 30 Hz] is like a slower vibe. It feels more like a square wave. And the other one [= 50Hz] is like a buzz. More like a continuous high vibration (...) like a phone vibration"* (P6).

In summary, the results of this study confirmed that the double-sided device could successfully provide index-only, thumb-only, or double-sided stimulation. Moreover, our device created a qualitative differences in tactile sensation between single-sided and double-sided stimulation, with the latter producing the sensation of "holding something in the middle of fingers".

5.2 Study 2: Assessing Finger-To-Finger Tactile Illusion of Movement

The spatiotemporal feedback across fingers is another crucial factor of double-sided tactile interactions, which we investigated in our second study. The goals of this study were: (1) to investigate whether apparent tactile motion between the two fingers occurred across our double-sided interface and (2) to clarify optimal parameters to elicit a continuous or discrete movement sensation.

5.2.1 Conditions. This study had two parameters: stimuli duration (DUR) and inter-stimulus onset asynchrony (SOA). This is informed by previous studies that showed DUR and SOA were the most significant parameters for apparent tactile motion [36, 56]. Similar to Study 1, we chose center electrodes (E_{f5} and E_{b5}) as the anode electrodes and used anodic pulses with a frequency of 50 Hz with a pulse width of 200 µs. 50 Hz was chosen to elicit a smoothly vibrating sensation, as shown in our first study. Only the front-to-back direction was examined, i.e., the index finger was stimulated earlier than the thumb every time, as the direction factor did not affect the perceived motion smoothness [36].

We chose two DUR (100 ms and 400 ms), informed by past studies [35, 36, 56]. For each DUR, we determined seven SOA values equally spaced in a range that was determined by our pilot study. In each range, the minimum was larger than our system's lower limit (1 ms) but resulted in no perception of motion, whereas the maximum resulted in the pilot participants perceiving two discrete stimuli [56]. For 100 ms DUR, SOA ranged from 11 to 191 ms. For 400 ms DUR, SOA ranged from 11 to 611 ms. In addition, the minimum SOA condition (1 ms) was added to check that participants felt simultaneous double-sided stimuli with the minimum SOA. Within one DUR, the index side of the double-sided interface is set to a linear ramp up and down in intensity at a time equal to 20 % of the stimulus duration to achieve smoother apparent motion [56].

Then, after the SOA, the thumb side will repeat the same for the next DUR.

5.2.2 Calibration. For each electrode, we calibrated the absolute tactile threshold and working amplitude. The absolute threshold was used as starting/ending points for ramp up/down. The amplitude was gradually increased from 0.5 mA, and the value at which the stimulus was first felt was set as the absolute threshold, and the value at which a clear, pain-free stimulus was felt was set as the working amplitude. Finally, the working amplitudes were adjusted so that the intensity felt in each finger was approximately the same. For the absolute threshold, the average amplitude values were 1.15 mA (SD = 0.24) for E_{f5} and 1.20 mA (SD = 0.20) for E_{b5}. For the working amplitude, the average amplitude values were 1.90 mA (SD = 0.27) for E_{f5} and 1.96 mA (SD = 0.24) for E_{b5}.

5.2.3 Trial Design and Procedure. The overall procedure followed past studies [35, 36, 56]. First, the participant experienced all trials and was asked in each trial if they "felt motion between fingers". Here, "motion" included both continuous and discrete stimuli. If they answered "no" to a trial, its rating was set to 0 (simultaneous). Second, the participant experienced again only the trials in which they answered "yes" to the first question and were further asked to rate the motion smoothness in each trial from 1 (discrete) to 7 (continuous). The trial was repeated until the participant had a clear answer. Each participant performed 48 trials (2 durations × 8 SOA × 3 repetitions) in a randomized order. After all the trials, we asked participants for qualitative feedback.

5.2.4 Results and Discussion. Figure 4 shows the average ratings as a function of SOA for each of the two durations, along with best-fit quadratic trends. The error bars show the standard errors of each mean. The peak location (a quadratic fit) for each duration was 117 ms (R^2= 0.90) for 100 ms duration and 337 ms (R^2= 0.87) for 400 ms duration. We obtained curve shapes that peak near the middle of the SOA range, similar to previous studies [35, 36, 56]. The average ratings at SOA = 1 ms were 0 (100 ms) and 0.17 (400 ms), confirming participants felt simultaneous double-sided stimulation at the minimum SOA. The ratings at each peak were 2.99 (100 ms) and 4.63 (400 ms). As in past studies [35, 36], near each peak, 400 ms duration generally elicited a more continuous sensation than 100 ms.

All participants used similar expressions to describe continuous and discrete stimuli. Continuous stimuli created the sensation of something traveling smoothly between fingers: *"felt like that [two stimuli] were sort of merged together and smoothly went from the index to the thumb. (...) It's a very unique sensation"* (P10) or *"it felt like something which started from here [= index] and (...) passed through the object and then came here [= thumb]. So it was like a message which came from this finger [= index] to this finger [= thumb]"* (P9). Since these descriptions were consistent with ATM observed in previous work [13], we confirmed that ATM can occur at a distance as short as our device's thickness (780 µm). Discrete stimuli were close to the sensation of something jumping between fingers: *"the more discrete one, it feels like a bug, like something jumping. (...) I felt like I was holding something and then the sensation moved across [fingers]"* (P6) or *"it's not continuous at all. It started on one and abruptly stopped on the other finger"* (P4).

Our second study concluded our double-sided device could (1) achieve apparent tactile motion (= continuous sensation) and (2) provide a simultaneous, continuous, or discrete sensation by appropriately selecting DUR and SOA. For simultaneous sensation, SOA close to the minimum value (1 ms) was optimal for both 100 and 400 ms DUR. For continuous sensation, the stimuli with a DUR of 400 ms and SOA of around 337 ms were optimal. For discrete sensation, the stimuli with a DUR of 100 ms, or ones with a DUR of 400 ms and SOA outside the ranges around a peak location and the minimum.

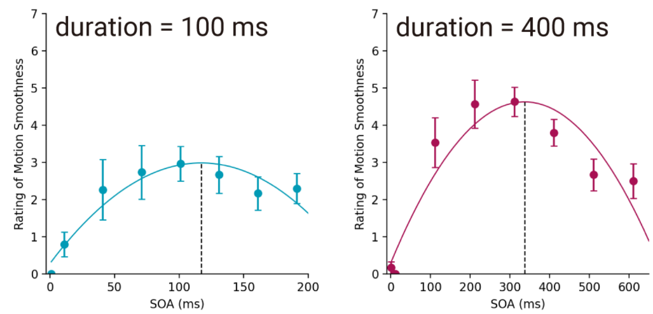

Figure 4: The average ratings of motion smoothness for each SOA in two durations (100 and 400 ms). The curve is a best-fit quadratic for the average values in each duration.

6 APPLICATIONS

We have implemented five VR applications to demonstrate potential applications of double-sided interactions during pinching in virtual reality: for representing virtual objects and for adding touch feedback to mid-air UI operation. We used a commercial VR head-mounted display (Meta Quest 1) and its hand-tracking function to detect the pinch gesture. The stimulation parameters have been set according to the outcomes of Study 2.

6.1 Representing a Virtual Object in-between Fingers

Our first category shows how double-sided interaction can represent a virtual object in-between two fingers.

A moving ladybug. As identified in the studies above, double-sided stimulation with our interface can elicit the sensation of something tiny moving in-between fingers. Figure 5 depicts our device rendering a ladybug's movement between fingers. (a) First, the ladybug is resting on the index finger's pad and rendered with one single-sided stimulus on the index finger (E_{f8}). (b) The user holds the ladybug lightly with the thumb and index, leading to double-sided stimulation of E_{f8} & E_{b8}, for feedback on both the thumb and index fingers. (c) The ladybug moves horizontally between the fingers, rendered by the along pattern of two stimuli that move laterally along the electrode array (E_{f8} & $E_{b8} \rightarrow E_{f5}$ & E_{b5}). (d) It finally starts flying and escapes from the fingers, making a discrete zigzag movement jumping between front and back sides and moving laterally ($E_{f5} \rightarrow E_{b2} \rightarrow E_{f2}$).

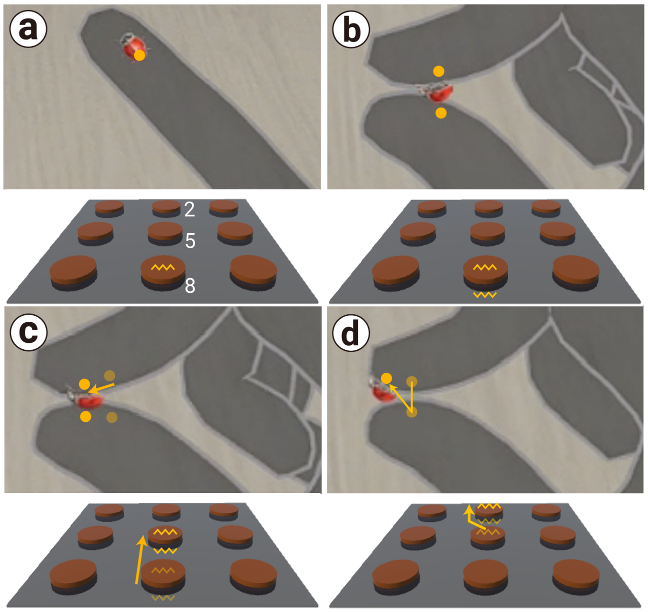

Figure 5: The double-sided interface renders a ladybug in virtual reality[1] (a) resting on the index finger, (b) held in-between the two fingers, (c) moving laterally between the fingers, and (d) flying and hitting the fingers alternately.

Rotating planets. Our aligned electrode layout between both sides enables rendering the rotation of a virtual object in three directions (pitch, yaw, roll). Figure 6 depicts the user playing a game in which the user can freely manipulate virtual planets in space. This application used a visuo-haptic effect, in which visual sensation often dominates over haptic sensation in perceiving shapes/sizes [1, 38, 47], for the interaction of picking a planet in VR while closing fingers in the real world, as depicted in Figure 6a. (a) The user grabs a blue planet with a small green island on the surface with fingers pointing horizontally. The island is rendered as a single-sided stimulus on the finger touching it. (b) The blue planet is rotating between fingers, and the island protrusion generates a rotation stimulation pattern that sequentially stimulates both fingers ($E_{b2} \longrightarrow E_{b5} \longrightarrow E_{b8} \longrightarrow E_{f8} \longrightarrow E_{f5} \longrightarrow E_{f2}$).

6.2 Adding Touch Feedback to Mid-Air UI Operation

Our second application category demonstrates how double-sided tactile interaction enhances tactile feedback to manipulate common mid-air user interfaces in VR. As a lack of haptic feedback in a user interface can reduce interface efficiency [2], researchers have explored adding a clicking/dragging sensation to mid-air UIs in VR [48, 51]. We demonstrate how our double-sided interface further extends these mid-air UI interactions.

Slider manipulation. Figure 7 depicts a user manipulating a slider to adjust the panel color saturation. (a) The user starts to hold the indicator of a slider. (b) When the user decreases the saturation and reaches the lower bound, they feel a single-sided stimulus only at E_{f5}, which is a tactile expression that the indicator stops at the lower limit. (c) Now, the user starts to increase the saturation and feels momentary double-sided stimuli only when they pass through slider ticks. (d) The user finally reaches the upper bound and feels a single-sided stimulus only at E_{b5} as another tactile stop expression.

[1]The numbers in the application figures denote the same electrode numbers as given in Figure 3a. In all the applications, the user holds the device so that E_{f2} & E_{b2} are positioned close to the fingertip and E_{f8} & E_{b8} close to the palm.

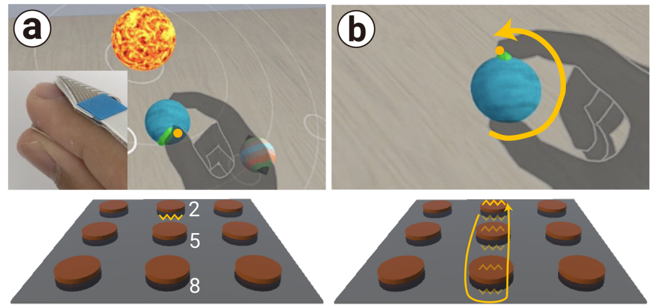

Figure 6: The double-sided interface renders rotary cues: (a) A slightly protruding island on a virtual planet generates a tactile cue that (b) slowly rotates across both pinching fingers in a spatiotemporal pattern. The user's fingers are actually pinched but rendered as detached fingers in VR.

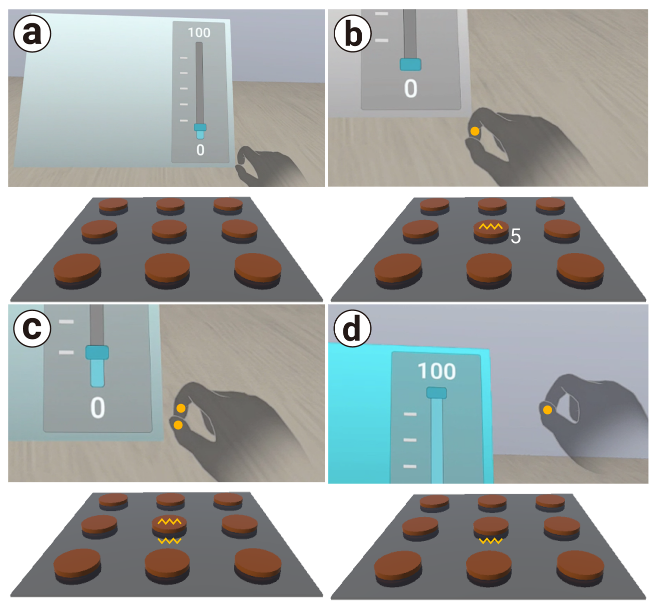

Figure 7: The double-sided interface enhances tactile feedback in slider manipulation in a VR environment. (a) The user holds an indicator of a slider. (b) When the slider reaches the lower bound, the user feels a single-sided stimulus on the front side, a tactile expression of the indicator's lower bound. (c) The user feels momentary double-sided stimuli when they pass through the ticks. (d) The user feels a single-sided stimulus on the back side at the upper bound as another tactile stop expression.

Selection in a pie menu. Figure 8 depicts a user manipulating a pie menu to select an icon. Our pie menu followed one of the UI designs commonly used in modern VR applications. With this design, the user points to an icon by pinching (a currently pointed icon is determined based on the straight line connecting the center of the menu and the pinched fingertips), moves the hand while pinching, and selects the target icon by releasing the pinch. We have implemented an example pie menu for a VR camera application. The pie menu is placed horizontally on the desk. Our device informs the user of the currently pointed icon by moving a stimulus according to the user's hand movement; this is a rotation pattern stimulation in active touch. (a) First, the user starts pinching and places their hand somewhere outside the pie menu to select a menu item. The temporally pointed icon is a "setting" icon, and E_{b2} is stimulated, indicating the direction of this icon. (b-e) The user moves their hand along the menu while pinching, and the position of the stimulus changes accordingly (E_{b1} for a "text" icon, E_{f4} & E_{b4} for a "camera" icon, and E_{b7} for a "profile" icon). (c) Important menu items (such as the main camera function in our example) can be tactually emphasized by rendering a pronounced cue on both sides of the device E_{f4} & E_{b4}. (e) Finally, the user reaches a "home" icon (E_{b8}) and selects it by releasing the pinch.

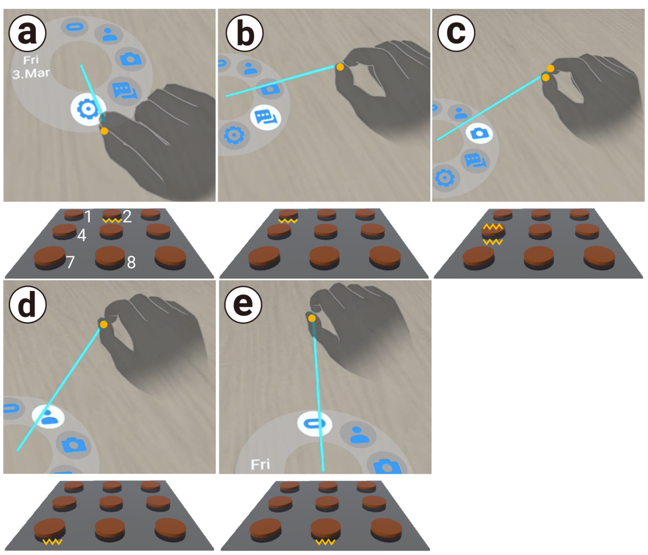

Figure 8: High-resolution double-sided tactile feedback enhances control of a pie menu in VR: (a) The user selects a menu element and gets tactile feedback indicating the direction of the selection made. (b, d, e) It changes dynamically with the selected menu element. (c) Important menu items can be tactually highlighted by rendering stimuli on both sides, generating a pronounced tactile sensation.

Pop-up effects. Figure 9 depicts a user interacting with a pop-up icon in a photo application. (a) The user picks up a photo with their dominant hand to see it more closely. (b) As the user looks at a photo, an icon with information related to the photo pops up. This visual pop-up effect is enhanced with a momentary animation with a continuous motion sensation from E_{f5} to E_{b5}. (c) After the user checks the information, they hide the icon by pushing it back with their non-dominant hand. The device renders an opposite animation a continuous motion sensation ($E_{b5} \rightarrow E_{f5}$).

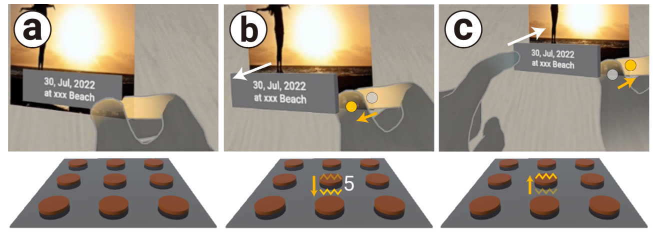

Figure 9: Pop-up effects are rendered by spatiotemporal stimulation between fingers. (a) When the user picks up a photo with their dominant hand and looks at it, (b) an information icon pops up, enhanced with momentary tactile animation with a continuous motion from the index finger to the thumb. (c) When the user pushes back the icon with their non-dominant hand, the icon dismisses with an opposite tactile animation to the dominant hand.

7 FURTHER INTERACTION SPACE

Our double-sided electrotactile device can be applied to stimulate not only a pair of two fingerpads but also combinations between various other skin areas throughout the body (e.g., palms, arms, legs, cheeks, lips, tongue, and even two people). Note that it is necessary to perform calibrations of pulse amplitudes for each body part since each part has a different absolute threshold in electrotactile stimulation [14].

One interesting future use case that stimulates multiple skin combinations is a whole-body double-sided stimulation system. Here, we assume the user attaches our double-sided device with a position tracker (e.g., OptiTrack) to their right index finger. When the user brings their index finger to each skin area (e.g., the left palm, the left arm, and the right cheek), the system adjusts the pulse amplitude to the appropriate value for each area and stimulates both skin sites.

8 LIMITATIONS AND FUTURE WORK

This first exploration of double-sided tactile interactions for pinched fingers has investigated only basic characteristics. Future research should investigate using frequencies other than 30/50 Hz and different frequencies on both sides. For assessing finger-to-finger tactile illusion of movement, future research could consider investigating other duration/SOA values, diagonal movements (e.g., $E_{f5} \rightarrow E_{b9}$), and integration with visual stimulation like [36]. Another direction is to evaluate the proposed interface using actual applications, such as how much it enhances the reality of the VR experience and improves task performance in UI operation.

This paper focused on simple VR applications to demonstrate the potential of double-sided tactile interactions. In addition to them, we also see promising application areas such as tactile cues in UI manipulation for the visually impaired, double-sided texture rendering, and changing output patterns according to the user's motion.

Our double-sided interface can provide double-sided tactile interactions only when fingers are closed. The interface's stacked form factor is only one option that focuses on providing co-located double-sided stimuli to the two fingers. The core double-sided tactile interactions can be used in other form factors as well, such as in a full-hand tactile interface [53] or in separated tactile interfaces attached to each finger [12], enabling double-sided feedback while pinching and single-sided feedback even while fingerpads apart.

Our applications detected an approximate pinching state with a hand-tracking function of the VR display, but a more precise touch-sensing method is needed to accurately detect touch contact and to suppress the sensation variability due to sweat or abrupt finger motion [15]. We plan to integrate a real-time skin impedance measurement function [11, 16] to check the touch state between the skin and each electrode. Another promising method is to incorporate a pressure sensor to control electrical stimuli in response to finger pressure [21].

Further minimization of the whole system should be considered, including a more conformal electrotactile interface [52, 53] and wireless communication.

9 CONCLUSION

We proposed a double-sided electrotactile device with a thin and flexible form factor to fit within pinched fingerpads. The device comprises two overlapping 3 × 3 electrode arrays to independently render the same or different stimuli on each fingerpad. We used this tactile interface to investigate double-sided tactile interactions with three feedback modes: single-sided, simultaneous double-sided, and spatiotemporal double-sided stimulation. Through two user studies, we (1) demonstrated that participants could accurately discriminate between single-sided and double-sided stimulation and found a qualitative difference in tactile sensation; and (2) confirmed the occurrence of apparent tactile motion between fingers and presented optimal parameters for continuous or discrete movements. In five VR applications, we illustrate how double-sided tactile interactions could produce spatiotemporal movement of a virtual object between fingers, such as (1) a moving ladybug and (2) rotating planets, and enrich touch feedback for UI operation, including (3) slider manipulation, (4) selection in a pie menu, and (5) pop-up effects. We believe double-sided tactile interactions open a very promising space for haptic interfaces, not only for fingerpads but also for various other skin areas throughout the body, including for instance palms, arms, cheeks, lips, and even tactile interaction between two people.

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