Vestibular Stimulation Enhances Hand Redirection

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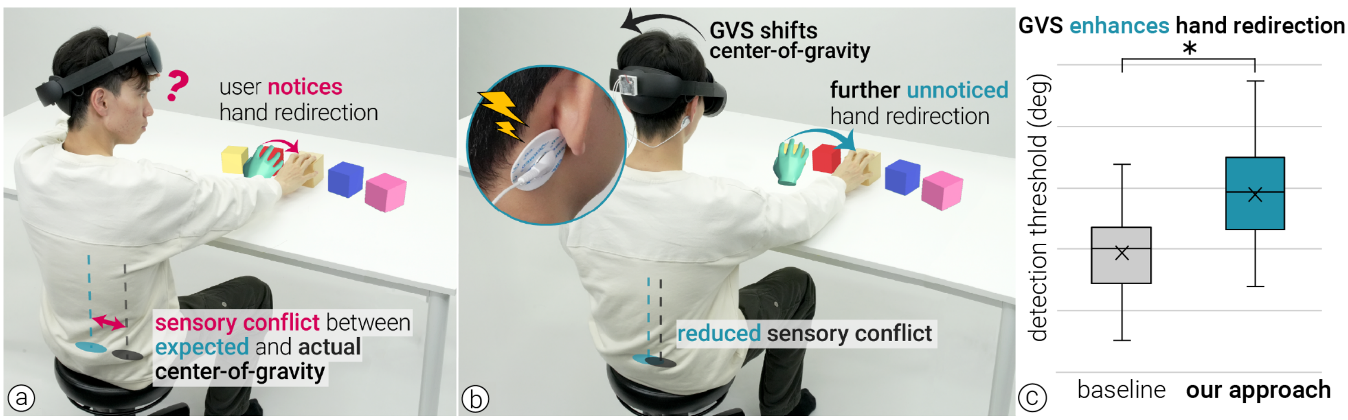

Figure 1: (a) Conventional hand redirection results in noticeable sensory conflicts due to mismatched visual and balance cues. (b) With GVS, we subtly shift the user's perceived balance toward the expected center-of-gravity (c) Our studies confirmed that our approach increases detection thresholds for VR hand redirection (the plot shows aggregated Study 2 results).

Abstract

We demonstrate how the vestibular system (i.e., the sense of balance) influences the perception of hand position in VR. By exploiting this via galvanic vestibular stimulation (GVS), we can enhance the degree to which we can redirect the user's hands in VR without them noticing, i.e., raising the detection threshold of hand redirection. Our novel cross-modal illusion relies on the principle that a GVS-induced subtle body sway aligns with the user's expected body balance during hand redirection. This alignment reduces the sensory conflict between the expected and actual body balance, allowing for a larger hand redirection than would normally be noticed. In our user study, we validated that our approach raises the detection threshold of VR hand redirection by approximately 55 % for outward and 45 % for inward movements. With this increase, our approach broadens the applicability of hand redirection (e.g., compressing a VR space into an even smaller physical area).

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CCS Concepts

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

Keywords

Galvanic Vestibular Stimulation, Hand Redirection, Virtual Reality, Haptics

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1 Introduction

Hand redirection (also known as *retargeting*) is a popular technique that leverages visual dominance—the brain's preference for visual over proprioceptive cues—to create compelling haptic illusions in Virtual Reality (VR). By subtly offsetting the user's virtual hand from its real-world position, hand redirection allows interactions with virtual objects using limited physical space or minimal haptic props [4, 7, 13, 18]. As with most illusions, hand redirection is limited by users *noticing* the sensory conflicts: when the discrepancy between the virtual and physical hand position exceeds a certain *detection threshold*, users *notice* the illusion which disrupts immersion [54, 58].

As such, the interactive potential of a hand redirection is mostly dictated by this detection threshold. In other words, the higher the detection threshold is, the more powerful the interactive applications of hand redirection will be. Unsurprisingly, since the inception of hand redirection more than a decade ago [38], most efforts have been aimed at *finding new ways* to *increase this detection threshold*.

Prior approaches to increase detection thresholds have involved, modifications of avatar appearances [51], leveraging blinks / saccades [66, 69], or cognitive distractions [68]–just to cite a few. While innovative, these techniques also introduce additional complexity and may require modifying VR content to accommodate specific situations.

In this paper, we propose a new way to mitigate a sensory conflict that users are likely to experience during hand redirection: a conflict between ***expected* center-of-gravity** (i.e., how their body-balance should feel if their hand was in the virtual hand's position) and ***perceived* center-of-gravity** (i.e., their current body-balance as determined by the actual hand's position). As depicted in Figure 1, we found that we can alleviate this sensory mismatch by *modulating* the user's vestibular sense with galvanic vestibular stimulation (GVS). In our novel technique, we apply GVS to induce a subtle body sway that aligns with the expected center-of-gravity. As found in our studies, this increases the detection threshold for hand redirection (up to ~55 % in outward redirection and up to ~45 % in inward redirection). As such, this technique provides researchers with a novel approach to amplify the interactive potential of hand redirection.

2 Related Work

We build on hand redirection and perceptual illusions. We review hand redirection methods and their key limitation—detection thresholds. Additionally, we introduce recent findings on how GVS influence perceptual thresholds.

2.1 Visual dominance enables VR illusions

Perception in VR relies on multisensory integration, where signals from different senses (e.g., vision, proprioception, vestibular, etc.) are combined [5, 10, 35]. When sensory conflicts occur, the brain typically prioritizes visual information [11, 21, 29, 58, 64]. This visual dominance has powered a number of VR techniques, such as pseudo-haptics [3, 16, 42, 55, 56], redirected walking [33, 37, 46, 57], and most relevant to our contribution, hand redirection.

2.2 Hand redirection

Hand redirection subtly offsets the user's virtual hand (in virtual space) from its actual position (in physical space). Due to visual dominance, users tend to adjust their hand's trajectory to match that of the virtual hand. This allows VR designers to enable richer interactions in space-constrained environments [4, 36]. For instance, as demonstrated by Kohli et al. in "redirected touching" [38], hand redirection enables a single prop to stand in for multiple spatially separated or shape-varied virtual objects [7, 71, 72]. The field continues to map the boundaries of this technique, exploring its application in bimanual interactions [23], the influence of avatar design [17], and adaptive control algorithms [22]—supported by comprehensive haptic taxonomies [49].

2.3 Detection thresholds

The key limitation of hand redirection is the detection threshold—the perceptual point when users consciously perceive discrepancies between virtual and real hand positions due to visuo-proprioceptive conflicts [15, 54]. At this threshold, visual dominance breaks down, and disrupts the user's immersion [24, 28, 47, 59]. Prior studies documented this breakdown, with participants commonly reporting feeling "disoriented," "confused," or "frustrated" upon noticing the manipulation [4, 13, 68]. Padrao et al. also demonstrated a significant reduction in sense of agency [54], underscoring detection thresholds as a barrier that bounds the effectiveness of hand redirection.

2.4 Overcoming detection Thresholds

One approach to addressing limited detection thresholds is to leverage attentional mechanisms. Examples include increasing redirection while the user is blinking [69], during saccadic eye movements [65], or both [66] (20.9 % increase in detection threshold as depicted in Figure 2). Similarly, distracting the user with audio-tactile/visual feedback or increasing task complexity [12] can also raise detection thresholds by diverting users' attention from the perceptual discrepancy. For instance, as shown in Figure 2, vibro-tactile and cognitive distraction resulted in increased detection thresholds [68]. However, these strategies typically introduce trade-offs such as increased cognitive burden and design limitations.

technique	increased detection threshold (outward | inward)	device
blink + saccade [66]	not measured | **20.9 %**	headset
tendon stimulation [50]	**6.7 %** overall	arm
audio-vibrotactile & visual cognitive distraction [68]	audio-vibrotactile: **27.3 %** | -39.5% visual cognitive: **63.6 %** | -23.7%	head
vestibular stimulation	**53.1 % | 43.6 %**	head

Figure 2: Key cross-modal approaches to increase detection thresholds in hand redirection. Values represent the percentage increase in detection threshold relative to each study's baseline.

Although visual dominance underpins hand redirection, relying solely on visual cues limits achievable detection thresholds—this is because the conflict is two-fold, visual (as seen by the eyes) and proprioceptive (as felt by the body, e.g., at joints, muscles, and so forth). Thus, recent efforts argue for a *cross-modal approach* to this sensory-alignment problem [30, 41, 62].

Methods such as noisy GVS applied in redirected walking [45], tendon vibration [30], and noisy tendon electrical stimulation [50] reduce the reliability of proprioceptive signals. By weakening this sensory channel, these techniques indirectly enhance visual dominance, thereby increasing the threshold at which users detect the discrepancies (e.g., 6.7 % increase in [50] as shown in Figure 2).

Alternatively, one can also raise perceptual thresholds by actively aligning the proprioceptive modality with visual illusions. This includes adding proprioceptive feedback to the user's legs via tendon electrical stimulation during redirected walking [52], or adding proprioceptive feedback to the wrist via hanger reflex during rotational hand redirection [62]. Notably, Hwang et al. demonstrated that actively modulating the vestibular sensation via GVS in redirected walking can increase the thresholds [31, 32]. Motivated by this, we integrate GVS into hand redirection, mitigating the sensory conflict in the sense of balance. This novel approach to modulating whole-body balance is distinct from haptic feedback only at the head/neck [27, 39, 40, 63].

2.5 Galvanic vestibular stimulation (GVS)

Galvanic vestibular stimulation influences the user's sense of balance via electrical currents on the vestibular system. When a low-intensity current (typically <3 mA [2]) is applied through electrodes attached behind the ears, it induces a vestibular sensation similar to being on a surface inclined in the direction of the current flow (left/right) [9, 19]. Consequently, it induces a reflex where the user's body tilts in the *opposite direction* to counteract this vestibular sensation to stabilize their body-balance [19]—it induces the left/right body sway opposite to the current flow [9, 19]. Aoyama et al. demonstrated that such body sways typically have a latency of ~3 seconds after the onset of the stimulation [2]. Since GVS only requires electrodes and a stimulator (no need for mechanical actuators), it has become a popular way to replace motion-platforms [1, 44]. Researchers explored the effect of GVS to reduce motion-sickness in VR [26, 61], increasing detection thresholds for redirected walking [31, 32, 45, 60], or enhancing the sense of walking in seated VR experiences [53].

3 Our Principle of Operation: Reducing Sensory Conflict via Galvanic Vestibular Stimulation

We now provide an account of the principle behind our approach. When we extend our limbs, it affects our body-balance by shifting the center-of-gravity [8, 34], and subsequently, the body readjusts to maintain stability and prevent falling [20]. We believe that the interaction between this mechanism of center-of-gravity shift and the effect of GVS offers one possible explanation for the working-principle of our approach. While proving the exact principle down to which brain mechanism is most affected by our cross-modal approach is beyond our scope, our *Study 1* empirically supports this principle.

Figure 3 (a) shows an illustrative plot of the user's center-of-gravity along the lateral axis over time (note that the figure exaggerates the balance shift for the sake of visual clarity). When the user extends the arm outwards from the torso to reach a target in VR, this causes a shift in their center-of-gravity. As they move outwards, they instinctively adjust their balance to stabilize (i.e., prevent from falling) [20].

Now, Figure 3 (b) shows how this leads to sensory conflict under hand redirection. Here, the user sees their virtual hand reaching outwards from their torso (depicted in blue). However, in reality, their arm is actually not extended much due to hand redirection, which is applied inwards. As a result, the user's *perceived center-of-gravity* does not shift, even though they *expected* a shift given visual information (i.e., they see their hand extended in VR). This mismatch between expectation and center-of-gravity sense leads to a sensory conflict (depicted in red). We believe this conflict in body-balance serves as a cue that *allows the user to detect the redirection*—thus limiting its detection threshold.

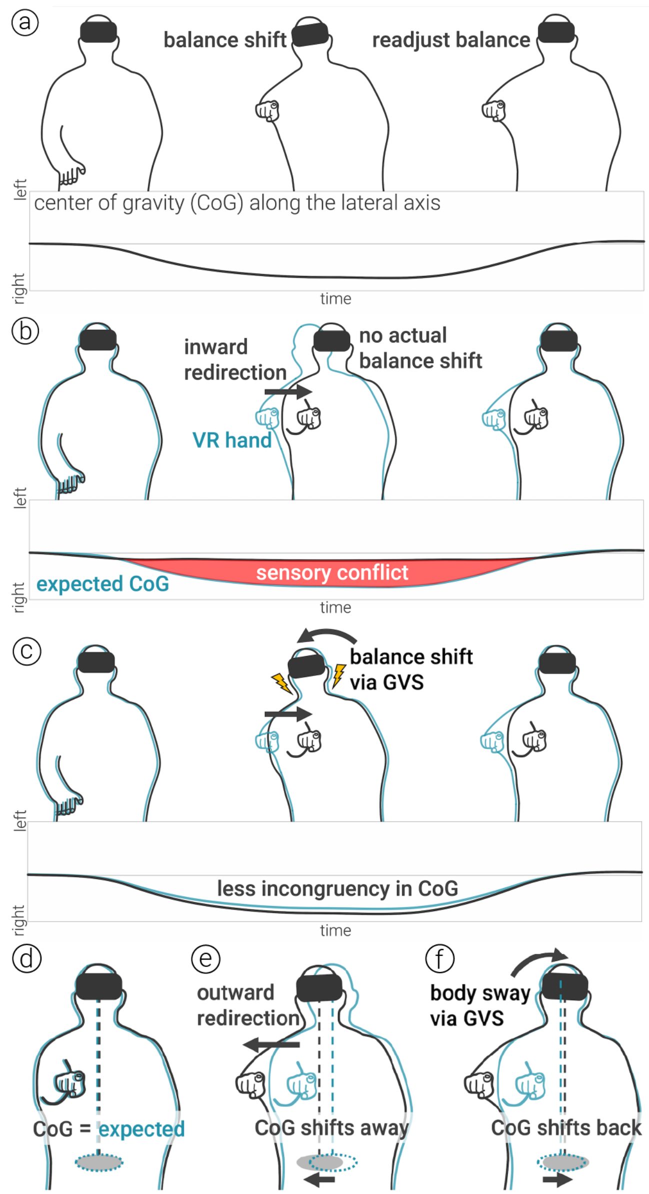


Figure 3: (a-c) Principle of our approach: mitigating the mismatch between expected and perceived center-of-gravity (CoG) shifts. (d-f) The principle similarly applies to outward redirection by shifting center-of-gravity (CoG) inwards.

Finally, Figure 3 (c) depicts how this sensory conflict is mitigated via GVS applied prior to the user's arm reach. As users encounter our GVS stimulation, they will reflexively adjust their posture in the opposite direction, creating a shift in their center-of-gravity—this shift aligns with the expectation where their center-of-gravity should be to best align with the position of the virtual hand. As depicted in Figure 3 (d-f), this also applies to redirection in the opposite direction, i.e., outwards to the torso. As we found in our user studies, this increased the detection threshold for hand redirection.

4 Study 1: GVS-Induced Balance Shift Extends Hand Redirection

The objective of our first study was to probe the working principle of our approach (see *Principle*). Our hypothesis was that a GVS-induced swaying of the user's body toward the expected center-of-gravity would increase the detection threshold of hand redirection. As such, we adopted a staircase procedure where we asked participants to perform reaching tasks under VR hand redirection across multiple GVS conditions. The study was approved by our Institutional Review Board (IRB23-0740, University of Chicago).

4.1 Interface conditions

To demonstrate that the enhancement of hand redirection was caused by GVS-induced sways towards the expected center-of-gravity—and not by confounding factors—we tested five interface conditions. All GVS stimulations started three seconds before the user began reaching, to compensate the time it takes for swaying the body [2].

Aligned-GVS (our approach): as the participant's hand was redirected, GVS would cause the participant's body to sway to the left via left-to-right constant current flow (i.e., towards the expected center-of-gravity—our hypothesis).

Opposite-GVS: control condition to test whether the direction of the shift matters. GVS swayed the participant's body to the right, deviating it from the expected direction.

Noisy-GVS: control condition to test for GVS effects unrelated to body sway, e.g., skin sensations from the stimulation. The stimulator applied white Gaussian noise across both polarities (i.e., a mean current amplitude of 0), which is known for not inducing body sways [48].

Sub-GVS: control condition to test for effects of vestibular stimulation without any perceivable sensation or induced body sway, using sub-threshold noisy GVS inspired by [45].

No-GVS: baseline condition for all GVS conditions. The participant experienced no stimulation.

4.2 Study design

Participants. We recruited 16 participants from our institution: 11 identified as male, four as female, one as non-binary; average=24.3 years old (SD=3.22); all right-handed. Each study session took approximately an hour. Participants received $10 for their participation.

Apparatus. The participant wore an HTC Vive headset with a Vive Tracker attached to the back of their right hand via an acrylic finger guide. The VR scene ran on a laptop with an AMD Ryzen 9 CPU and an NVIDIA RTX 3080 GPU, using Unity3D. For GVS, the participant wore two electrodes behind each side of the ears (the mastoids), connected to Liu et al.'s open-source stimulator [43]. Finally, we used *Hand-Redirection-Toolkit* [67] and *Staircase-Procedure-Toolkit* [70] to manage tasks and procedures.

Tasks. The participant was immersed in a VR scene depicted in Figure 4 (a)—a similar environment to [68]. In each trial, they first placed the right index fingertip at the initial position, seeing the prompt "Get ready!". After a random delay (up to 5 seconds), the stimulator began applying GVS at the pre-calibrated intensity, whose amplitude remained fixed throughout all trials and independent of the redirection magnitude. Then, after a fixed 3-second delay from GVS onset, the prompt switched to "Go!", signaling to reach towards a target cube. As shown in Figure 4 (b), during the reach, the participant's real hand (not visible to the participant) was redirected outward relative to the VR hand (as in [66]), following Cheng et al.'s method [7]. The GVS ran concurrently with this redirection and stopped when the hand reached the target. Then, the participant answered: "Did you feel a positional offset between your virtual and physical hands?" [yes/no]. According to their response, the degree of hand redirection for the next trial was determined (via staircase procedure).

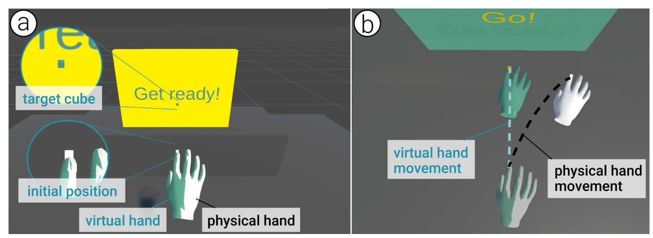


Figure 4: Our reaching task with VR hand redirection. (a) The participant initially waited for the "Go" prompt. (b) During the reaching movement. The white hand representing the real hand was for illustrative purposes only and was not visible to the participant.

GVS calibration. Prior to the trials, we calibrated GVS for each condition by gradually increasing the intensity. For *aligned-GVS* and *opposite-GVS*, we increased the intensity in 0.4 mA increments to find the minimum level at which a 5-second stimulation induced more than 2° of body tilt (measured by the headset) three consecutive times. For *noisy-GVS*, we similarly used 0.4 mA increments to set the intensity to the maximum level within the participant's comfort range. For *sub-GVS*, we first identified the perceptual threshold using 0.1 mA increments, and set the intensity to 0.1 mA below that threshold. Note that we instructed the participant not to voluntarily move their body/head during this calibration. The stimulation intensity, once calibrated, remained fixed throughout all trials.

Calibration results. Across the conditions, our participants were calibrated to the following average GVS intensities: *aligned-GVS*=1.28 mA (SD=0.72); *opposite-GVS*=1.25 mA (SD=0.69); *noisy-GVS*=1.73 mA (SD=0.65); and *sub-GVS*=0.28 mA (SD=0.08).

Procedure. Participants completed five condition blocks in a randomized order. Within each block, they performed two interleaved staircase procedures in a randomized order: (1) the initial trial was set to 0° redirection, i.e., no redirection; and (2) the initial trial was set to 16° redirection. This resulted in a total of 10 staircase procedures (5 GVS conditions × 2 staircase configurations). Within each condition block, the participant first completed practice trials to familiarize themselves with the task: a trial without redirection or GVS, followed by another no-redirection trial but with GVS, and then a trial with clearly noticeable redirection (30°) with GVS. Afterward, they performed actual trials under the staircase procedures where the degree of hand redirection was adaptively altered according to the participant's response after the reaching task by ±3°. Each staircase procedure concluded after the participant reversed their response five times. The redirection angles at these reversal trials were averaged to determine the detection threshold. Finally, at the end of each condition, they rated the comfort of the GVS-induced sensations on a 7-point Likert scale (1: not comfortable at all; 7: completely comfortable).

4.3 Results

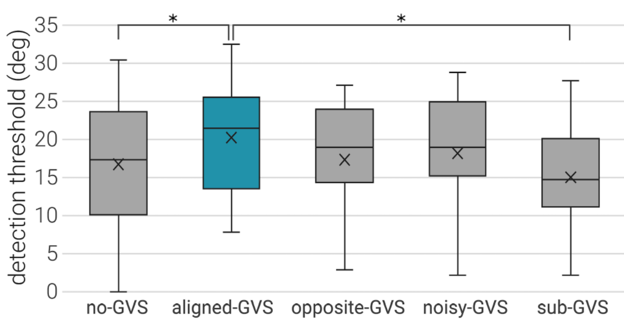


Figure 5: Participants' detection thresholds. Statistically significant comparisons are indicated by asterisks (*: p<0.05).

Figure 5 shows the average detection thresholds across all conditions—*no-GVS*: M=17.11 (SD=9.71); *aligned-GVS*: M=20.65 (SD=9.34); *opposite-GVS*: M=17.61 (SD=8.44); *noisy-GVS*: M=18.47 (SD=8.66); and *sub-GVS*: M=15.24 (SD=7.70). Shapiro-Wilk tests confirmed normality for all conditions. Thus, we conducted a one-way repeated measures ANOVA, revealing a significant effect of conditions ($F(4,60)$=4.923, η_p^2=0.049, p=0.0083). The p-value was based on Greenhouse-Geisser correction as Mauchly's test indicated sphericity violation. Post-hoc pairwise comparisons using Bonferroni correction indicated that ***aligned-GVS* increased detection thresholds compared to *no-GVS* (p=0.049) and *sub-GVS* (p=0.045)**, while not finding significant comparisons between other GVS conditions and *no-GVS*. This confirmed our hypothesis.

Subsequently, we analyzed the comfort ratings: *no-GVS* (M=7.00, SD=0); *aligned-GVS* (M=4.56, SD=1.67); *opposite-GVS* (M=4.75, SD=1.53); *noisy-GVS* (M=4.06, SD=1.34); and *sub-GVS* (M=6.81, SD=4.03). Shapiro-Wilk tests indicated that *sub-GVS* violated normality (W=0.484, p<0.001). Thus, we proceeded with the Friedman test, which revealed a statistically significant difference in comfort levels among the conditions ($\chi^2(4)$=46.5, p=<0.001). Post-hoc comparisons using the Wilcoxon signed-rank test with Bonferroni correction found significant differences between the following: *no-GVS* vs. *aligned-GVS* (Z=-1.91, p=0.010); *no-GVS* vs. *opposite-GVS* (Z=-1.91, p=0.010); *no-GVS* vs. *noisy-GVS* (Z=-3.52, p=0.004); *sub-GVS* vs. *aligned-GVS* (Z=-3.52, p=0.015); *sub-GVS* vs. *opposite-GVS* (Z=-3.52, p=0.010); and *sub-GVS* vs. *noisy-GVS* (Z=-3.52, p=0.004).

Result discussion. Our results confirmed that swaying the user's body via GVS in the *expected center-of-gravity* direction (i.e., *aligned-GVS*) increases detection thresholds in hand redirection. The finding supports the underlying mechanism of our approach described in *Principle*. We also observed a significant difference in the detection threshold between *sub-* and *aligned-GVS*, which suggests that *sub-GVS* might have enhanced vestibular sensitivity (possibly via stochastic resonance [45]).

5 Study 2: Directionality & GVS Timing

The goal of this second study was to evaluate the applicability of our approach under broader conditions of hand redirection. Specifically, we focused on two questions: (1) Does our approach work for hand redirection in the other direction along the horizontal axis (i.e., inward movements)? and (2) How do different preemption durations (i.e., the time GVS onset precedes hand movement onset) affect our approach? We explored these questions using a protocol similar to *Study 1* but focused on comparing *aligned-GVS* (with varied onset timings) to a *no-GVS* baseline while also adding a reaching task with redirection in the other direction. The study was approved from our Institutional Review Board (IRB24-172, University of Tsukuba).

5.1 Interface conditions

To evaluate the effect of varying the onset of GVS stimulation, we introduced three timing conditions—**0-sec** (GVS starts at the onset of the hand motion cue); **1.5-sec** before the onset; and **3.0-sec** before the onset (same as *aligned-GVS* from *Study 1*). As a baseline we also featured a *no-GVS* condition (no stimulation applied).

5.2 Study design

Participants. We recruited 16 participants from our institution: 13 identified as male, 3 as female; average=23.3 years old (SD=2.12); all right-handed. None of them had partaken our first user study. Each study session took approximately 1.5 hours.

Apparatus. We had the same apparatus as *Study 1*.

GVS calibration. As in *Study 1*, the GVS intensity was calibrated per-participant and remained fixed throughout the experiment. The GVS onset timing, in contrast, was the primary independent variable systematically varied across conditions (0, 1.5, and 3.0-seconds). Additionally, the direction of *aligned-GVS* was set to induce leftward body sway for outward redirection and rightward body sway for inward redirection, based on our principle (Figure 3c-f).

Tasks. The participant performed the same reaching task used in *Study 1*, but under different GVS onset timings. The participant also experienced two types of hand redirection: (outward redirection) as in *Study 1*, the real hand was redirected outward relative to the VR hand, depending on the staircase procedure (Figure 6a); and (inward redirection) the VR hand was redirected outward relative to the real hand, depending on the staircase procedure (Figure 6b), i.e., the real hand was redirected inward relative to the VR hand. Note that these hand-redirection configurations followed prior work [50, 66]. In outward redirection, GVS induced leftward body sway for the expected center-of-gravity shift (Figure 3f). In inward redirection, GVS induced rightward body sway based on our principle (Figure 3c).

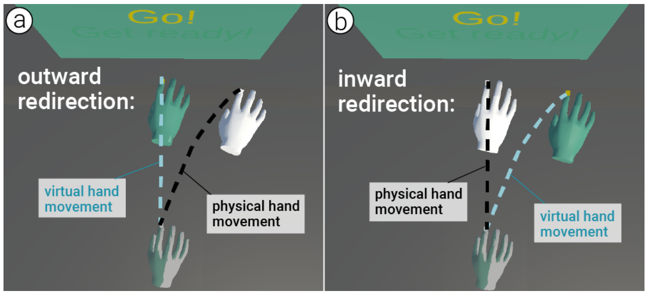


Figure 6: The reaching task with outward (a) and inward hand redirection (b). The blue/white hands represent VR/real hands, respectively. The white hand was not visible to the participants.

Procedure. We leveraged the same procedure as in *Study 1*. Participants completed eight experimental blocks (4 conditions × 2 redirection types) in a counter-balanced order using Latin square. Within each block, they performed the two configurations of interleaved staircase procedures in a randomized order. This resulted in a total of 16 staircase procedures (4 conditions × 2 redirection types × 2 staircase configurations). Additionally, we elicited the participant's qualitative feedback on their experience at the end of each condition block by asking, "Could you tell us about your experience during the trials?".

5.3 Results

Figure 7 shows the average detection thresholds across all conditions. Shapiro-Wilk tests confirmed normality for all conditions under both hand-redirection types. Mauchly's test indicated no violations of sphericity. A two-way repeated-measures ANOVA showed no significant main effect of condition (F(3,45)=2.42, η_p^2=0.139, p=0.078) or redirection type (F(1,15)=0.78, η_p^2=0.049, p=0.391), and no significant interaction (F(3,45)=0.17, η_p^2=0.011, p=0.918).

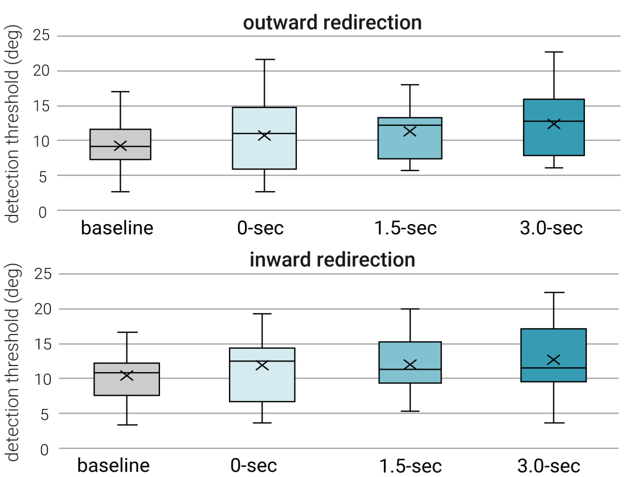
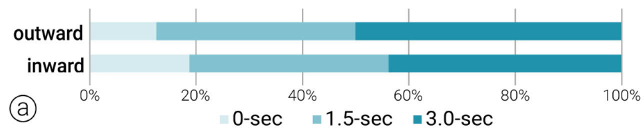


Figure 7: The distribution of participants' detection thresholds in outward (a) and inward (b) redirection scenarios.

However, while this suggests there is not a *one-size-fits-all* timing that works *across* all participants in our study, there is a chance of *per-participant* timing conditions that might increase the detection threshold. This is what we explore next. Figure 8 (a) shows the results of our follow-up analysis where we selected the GVS condition that yielded the highest detection threshold per-participant, we denote this as *timing-calibrated-GVS*, i.e., best-case onset timings for each participant. The specific timings chosen for each participant is detailed in Figure 8 (b): 8 out of 16 participants had identical optimal timings for both directions, while the others differed by only one step (i.e., none had 0-sec and 3.0-sec).



participant	P1	P2	P3	P4	P5	P6	P7	P8
outward	0-sec	1.5-sec	3.0-sec	3.0-sec	1.5-sec	1.5-sec	1.5-sec	3.0-sec
inward	1.5-sec	1.5-sec	1.5-sec	3.0-sec	3.0-sec	0-sec	0-sec	1.5-sec
participant	**P9**	**P10**	**P11**	**P12**	**P13**	**P14**	**P15**	**P16**
outward	1.5-sec	3.0-sec	0-sec	3.0-sec	3.0-sec	1.5-sec	3.0-sec	3.0-sec
inward	3.0-sec	3.0-sec	0-sec	3.0-sec	3.0-sec	1.5-sec	1.5-sec	3.0-sec

(b)

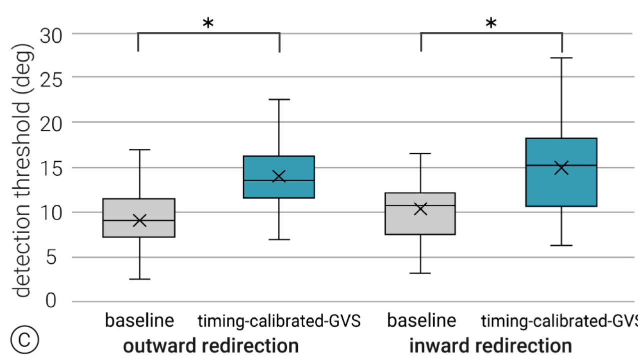


Figure 8: (a) Makeup of timing-calibrated-GVS, points selected to maximize per-participant detection threshold. (b) A per-participant breakdown of timing-calibrated-GVS. (c) Detection thresholds of baseline and timing-calibrated-GVS (*p<0.05).

To determine whether this *timing-calibrated-GVS* dataset is statistically different from *baseline*, for each movement direction, we conducted permutation tests [25] using Holm's correction. We avoided using parametric tests (e.g., t-tests), which could inflate the Type-I error rate [6]. We ran 5,000 iterations of these permutations. In each iteration, we compared the difference in mean detection thresholds for our key comparison (i.e., $\mu_{timing-calibrated-GVS} - \mu_{baseline}$) against a mean difference obtained by the following procedure: (1) shuffling the condition labels (*baseline*, *0-sec*, *1.5-sec*, and *3.0-sec*) for each participant; (2) define *timing-calibrated-GVS* and *baseline* based on this new label assignment; (3) calculate the mean difference between them. By repeating this process, we could statistically assess how often our key comparison was exceeded by comparisons based on a random assignment. Our permutation test used a 95 % significance level (p=0.05). We found that the comparison between *timing-calibrated-GVS* and *baseline* was significant: p=0.011[1](outward) and p=0.049 (inward). Finally, Figure 8 (c) depicts the contrast between *baseline* and *timing-calibrated-GVS* in the outward (*baseline*: M=9.2, SD=3.4 vs. *timing-calibrated-GVS*: M=14.1, SD=4.2) and inward redirection (*baseline*: M=10.5, SD=3.5 vs. *timing-calibrated-GVS*: M=15.1, SD=5.2). Putting these results together, we found that per-participant *timing-calibrated-GVS* can increase the detection threshold by 53.3 % for outward redirection and about 43.8 % for inward redirection.

Qualitative feedback. 10 out of 16 participants mentioned perceiving body sways while reaching for targets. Five participants stated they got used to this sensation. For example, one noted, "Compared to the first time, (...) I wasn't aware of [the sensation] because [the sway started to feel] more natural," and another stated, "I didn't notice [the body sway] as much as before". Two participants reported skin sensations caused by the stimulation, but both said they eventually got used to it. One participant commented, "It was a little surprising at first, but at some point, I got used to it".

Result summary. Our results did not confirm that a *fixed-GVS onset timing* can increase the detection threshold across all participants. Yet, further analysis suggests that, by using a per-participant onset timing, our approach can improve the detection thresholds of hand redirection by up to ~55 % and ~45 % for outward and inward redirection, respectively.

6 Discussion

Practical Significance. Assuming a typical 40 cm arm reach, the ~5° gain in the detection threshold observed in our studies corresponds to expansion of an interaction space by ~140 cm^2. Our approach also supersedes prior techniques that rely on change blindness (e.g., ~2.8° from avatar appearance [51] and ~1.8° from blinks/saccades [66]) or sensory noise (e.g., ~1.3° from tendon stimulation [50] and ~1.2° from audio-vibrotactile [68]). It is also notable that prior GVS work in redirected walking has also shown a comparable gain (~35 % improvement over a baseline) to our approach (45~55 %) [31]. These results across different task domains underscore that modulating perceived body balance is an effective method for modulating spatial perception.

Calibration Guidelines. Our technique requires per-user calibration of GVS intensity and onset timing. Drawing on our studies, we propose the following guideline: (1) find the minimum GVS intensity that reliably produces a desired body sway (e.g., >2°); (2) run staircase procedures using that intensity while varying the GVS onset timing (e.g., 0-, 1.5, 3.0-sec); (3) select the onset time that yields the highest detection threshold for that user; and (4) repeat for both redirection types (i.e., inward and outward).

[1]In the context of a permutation test, a p-value of 0.011 indicates that our comparison ($\mu_{timing-calibrated-GVS} - \mu_{baseline}$) was defeated by another random comparison, only 55 times (of 5000). Same applies for next p-value.

7 Application: Expanding VR Space

To illustrate the applicability of our approach, we depict two applications that make use of our GVS-enhanced hand redirection. These applications run on a Quest Pro headset.

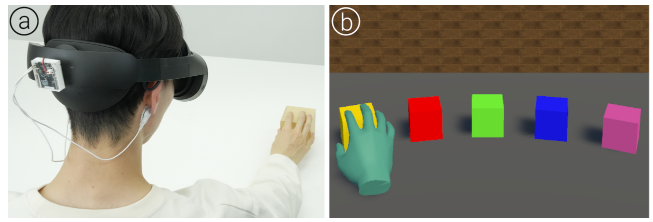


Figure 9: A single physical prop represents five virtual cubes—our replication of "Haptic Retargeting" [4] but with a larger virtual space compressed into the same prop.

Figure 9 shows how our approach replicates the seminal "Haptic Retargeting" [4] demonstration. With the increased detection thresholds from our method, a single prop now represents *five* virtual cubes, as opposed to *three* in the original demo. This illustrates how our approach further expands the applicability of passive-prop haptic interactions.

Figure 10: The user's hand interacts with VR widgets in a much smaller physical area confined by the wall and the laptop.

Our approach also enables larger VR workspaces to be compressed into much smaller physical areas. As shown in Figure 10, the user interacts with virtual windows placed in front of them, even though their available physical workspace is confined between a wall and a laptop. This illustrates how our approach could potentially expand hand-redirection applications to space-constrained environments, such as airplane seats, crowded transit, or small desk areas.

8 Limitations and Future Work

Our approach is not without limitations. First, our sample size (N=16 per study), while typical for psychophysical studies in this domain, may not capture the full spectrum of responses. Additionally, as with any GVS-based technique, it requires per-user calibration. It is reported that GVS can induce a tingling sensation (similar to electro-tactile) at the electrode sites; however, in our *Study 2* interview, only two (out of 16) participants explicitly reported this sensation. Moreover, due to the known delayed onset of GVS [2], the stimulation must be initiated preemptively relative to the user's motion, which we have shown can be optimized per-user. Our investigation was limited in its range of motion; as we employed Cheng et al.'s method [7] for redirecting the hand along the horizontal movement axis, we have not yet tested other directions/rotations. However, it is worth noting that the vast majority of work in hand redirection focuses primarily horizontal movement axis [50, 51, 68]. Finally, because our approach depends on shifting the user's center-of-gravity while seated with an upright torso, it may not generalize to some postures (e.g., lying down, reclining, etc).

A key future work direction is to investigate dynamic GVS amplitude modulation, responsive to a user's real-time hand reach dynamics, to further enhance the illusion's strength and comfort. To increase the practicality of our approach, the current calibration procedure could be also automated based on center-of-gravity tracking. Another possibility to accelerate the calibration is to incorporate an adaptive threshold estimation technique [14] into our approach. Furthermore, exploring whether the idea of "aligning the user's center-of-gravity" could be applied to hand redirection using other balancing-methods (e.g., motion-platforms).

9 Conclusions

We demonstrated that even balance can affect the detection thresholds of hand redirection in VR, due to mismatches between one's expected center-of-gravity from VR's visual information and one's perceived center-of-gravity from one's vestibular sense. We proposed and validated a new way to mitigate this sensory conflict by "pushing" the user's vestibular sense towards the expected center-of-gravity, achieved by means of galvanic vestibular stimulation (GVS).

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