Investigating Movement-Related Tactile Suppression Using Commercial VR Controllers

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Abstract. When we perform a goal-directed movement, tactile sensitivity on the moving limb is reduced compared to during rest. This well established finding of movement-related tactile suppression is often investigated with psychophysical paradigms, using custom haptic actuators and highly constrained movement tasks. However, studying more naturalistic movement scenarios is becoming more accessible due to increased availability of affordable, off-the-shelf virtual reality (VR) hardware. Here, we present a first evaluation of consumer VR controllers (HTC Vive and Valve Index) for psychophysical testing using the built-in vibrotactile actuators. We show that participants' tactile perceptual thresholds can generally be estimated through manipulation of controller vibration amplitude and frequency. When participants performed a goal-directed movement using the controller, vibrotactile perceptual thresholds increased compared to rest, in agreement with previous work and confirming the suitability of unmodified VR controllers for tactile suppression research. Our findings will facilitate investigations of tactile perception in dynamic virtual scenarios.

1 Introduction

When we perform a movement using a specific body part, sensitivity to external tactile stimuli on this body part is substantially reduced [6,7]. This *tactile suppression* effect has now been reliably established for a variety of self-generated movements, such as single finger abductions [6,7], goal-directed reaching [5,9,11,18,19], and grasping [15]. It is commonly attributed to central mechanisms that predict sensory action outcomes using a feed-forward model and suppress corresponding afferent sensory inputs [1,20], although peripheral mechanisms such as masking may also be involved [6]. Tactile suppression phenomena are a useful avenue to study predictive processing in the human sensorimotor system [10] and in understanding the informational value of tactile feedback during active movement.

Tactile sensitivity is usually investigated using specialized haptic actuators ("tactors", cf. [8,14] for review), which can be expensive and require special

expertise to use. At the same time, many research labs now have virtual reality (VR) setups at their disposal due to advances in consumer hardware, and research is shifting towards freely moving participants in virtual environments. Consumer VR hardware bundles typically include wireless game controllers, most of which now feature a built-in vibrotactile actuator for haptic feedback. Consequently, leveraging built-in vibrotactors for behavioral research would facilitate studying tactile sensitivity in freely moving participants and without the need for custom tactile stimulation devices. However, the exact haptic properties of these controllers are largely undocumented. Here, we evaluate two commercially available VR controllers (HTC Vive and Valve Index, cf. Fig. 1) to determine whether a controller's vibration amplitude (stimulus intensity) can be controlled finely enough to measure tactile perceptual thresholds using psychophysics. Additionally, we compare tactile detection thresholds between a resting baseline and a simple goal-directed movement task to assess the suitability of this setup for the detection of movement-related tactile suppression. Moreover, the tested controllers allow for specifying vibration frequency. Human tactile perception integrates a combination of four main sensory channels with different temporal and spatial sensitivity profiles [2,12,13]. Because of spatial summation effects due to the relatively large physical size of the controllers and differences in hand posture, it is unclear how different actuator frequencies propagate to the participant's skin surface. We thus further compare perceptual thresholds for three different frequencies (100, 250, and 400 Hz) to investigate possible frequency-dependent differences in haptic perception when using VR controllers.

2   Methods

2.1   Participants

A total of 19 participants took part in the experiment. Data from one participant were excluded due to excessive movement in the baseline condition, leading to a total sample of 18 participants (13 female, 5 male; mean age 25.1 years ± 4.9 years, range 19–37 years). All participants were right handed as confirmed using the Edinburgh Handedness Inventory (EHI [16]; mean score 83.2, range 33–100) and had normal vision or corrected-to-normal vision using contact lenses. Participants gave written informed consent and received course credits or 8€ per hour for their participation. The experiment was approved by the research ethics board at Justus Liebig University Giessen (protocol number 2019-0003) and was performed in accordance with the Declaration of Helsinki (2008).

2.2   Apparatus

Participants sat on a desk chair without armrests, with both arms hanging at their sides in a relaxed position and holding a VR game controller in each hand. Two different controllers were used, as shown in Fig. 1 (left): the HTC Vive Pro controllers[1] (hereafter: *Vive*; HTC Corp., Xindian, New Taipei, Taiwan) and

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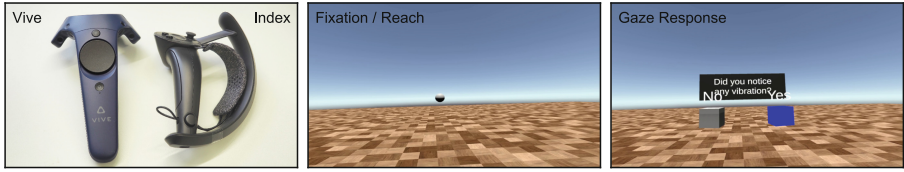[1] https://www.vive.com/eu/accessory/controller2018/.

Fig. 1. *Left*: Controllers used in the study (HTC Vive Pro and Valve Index). *Middle*: Target sphere in VR (fixation or reach target, depending on the condition). *Right*: Gaze response procedure. The participant selected the right cube ("Yes") in this trial.

Valve Index controllers[2] (hereafter: *Index*; Valve Corp., Bellevue, WA, USA). In each experimental session, participants held controllers of the same type in both hands to keep muscle activation and somatosensory feedback across both hands comparable. Only the right controller was used for movement and vibrotactile stimuli. Participants wore an HTC Vive Pro Eye HMD, used to present task instructions and collect participants' responses using the integrated eye tracker.

Participants were presented with a minimal visual scene consisting of a tiled floor and sky (Fig. 1). Instructions were presented as light gray text on a dark background panel which floated in front of the participant. No 3D models of the controllers were rendered in the VR environment, because pilot testing determined that stronger vibrotactile stimuli could cause visible jitter in the controller model, potentially yielding a visual cue for whether a vibrotactile stimulus was present or absent[3]. Auditory pink noise was played over the HMD's headphones to ensure that participants based their responses only on the vibrotactile stimuli and not on audible noise from the haptic actuator. The experiment was implemented using Unity (version 2019.4.16f1; Unity Technologies, Inc., San Francisco, CA, USA), SteamVR (version 1.20.1), the Vive SRanipal eye tracking framework (version 1.1.2.0), and the Unity Experiment Framework [4]. It was run on an Alienware desktop PC (Intel Core i9-7980XE CPU at 2.6 GHz, 32 GB RAM, Dual NVidia GeForce GTX1080 Ti GPU).

2.3 Experimental Task

Participants performed a *movement* condition, in which they had to execute a reaching movement towards a visual target using the controller in their right hand, and a *baseline* condition, in which they had to simply hold the controllers at their side without moving. Movement and baseline conditions were run as separate consecutive sessions. Each trial started with the presentation of a light gray sphere (distance 1.5 m, radius 5 cm; cf Fig. 1, middle) at eye level and at a

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[2] https://www.valvesoftware.com/de/index/controllers.

[3] Presumably, this is due to the inertial measurement unit within each controller, which is used for positional tracking and can become overwhelmed by noise when vibrotactile feedback is activated.

random angle ($\pm 20°$) from the participant's body midline. In the movement conditions, a vibrotactile stimulus of 200 ms duration and with varying amplitude and frequency was presented using the right controller at movement onset, which was determined online using a movement speed criterion (0.3 m/s). If a participant failed to move within 3 s after sphere onset, a reminder text appeared and the trial was excluded from analysis. In the baseline condition, the vibrotactile stimulus was always applied after a fixed delay of 500 ms after sphere onset and participants had to simply fixate the sphere. They were instructed to let their arms hang at their sides instead of resting them on their leg to avoid additional tactile perception on their thigh or knee. After each trial, participants were asked whether they felt a vibration of the right controller. To avoid confounding their response with the stimulated limb, such as by using a controller button press, responses were collected using the eye tracker in the HMD. Two light gray cubes (distance 1.5 m, side length 20 cm, Fig. 1, right) were shown at eye level, labeled with the text "Yes" and "No" alongside the question "Did you notice any vibration?". Participants responded by looking at the cube corresponding to their chosen response for 1 s, after which the selected cube changed color to indicate the chosen answer. The eye tracker was calibrated at the start of each session using the built-in calibration routine.

Vibrotactile stimuli were presented at three possible frequencies (100, 250, and 400 Hz) and at seven possible intensities (0.00001, 0.0001, 0.001, 0.01, 0.1, 1.0, and no stimulation)[4]. Each frequency and stimulus intensity combination was repeated eight times, leading to a total number of 168 trials per session (3 frequencies × 7 intensities × 8 repetitions). Each session took around 12 min to complete, and each participant performed four sessions in total (one movement and one baseline session per controller type). Sessions using the same controller type were performed consecutively. The order of controllers was counterbalanced across participants, as was the order of baseline and movement sessions within each controller type. The full experiment took around one hour.

2.4   Data Analysis

Data analysis was performed using Python (version 3.8) and jamovi (version 2.2.3). Trials in which participants did not move in the movement condition, or performed a movement in the baseline condition, were excluded from the dataset (57 trials or 0.47% total). Psychometric functions were then fit to each participant's rate of "yes" responses (detection rate) per stimulus intensity using the psignifit 4 toolbox [17]. Initially, functions were fit to all response data per condition, independent of the presented frequency to gain a robust estimate of individual response behavior. This *combined analysis* thus contained 24 responses per stimulus intensity (3 frequencies × 8 repetitions). As stimulus intensity levels ranged from 10^{-5} to 1 in steps of one order of magnitude, data were fitted with

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[4] Intensity values are provided to SteamVR on a scale of zero to one and do not directly correspond to any physical property such as peak-to-peak displacement.

a Weibull psychometric function and perceptual thresholds (stimulus intensities at which a participant would have a detection rate of 0.5) are thus returned on a log scale. Since a stimulus intensity of zero is not defined on a log scale, response rates in trials without a stimulus (false alarms) were set as a fixed lower bound (gamma parameter) when fitting each participant's psychometric function for each condition. Individual false alarm rates ranged from 0–0.33 (mean: 0.07) in the baseline and 0–0.21 (mean: 0.05) in the movement condition.

To assess tactile suppression, we calculated threshold difference values by subtracting each participant's baseline detection threshold from their movement threshold, separately for each controller type. Due to the log-scaled intensity values, a threshold difference value of 1 indicates a difference of one order of magnitude in stimulus intensity. To test for suppression, we then used one-sample t-tests to compare these threshold differences against zero. To compare suppression effects and baseline detection thresholds between controllers, we used paired t-tests where data were normally distributed (Shapiro-Wilk test), otherwise the Wilcoxon signed-rank test was used. To further investigate effects of controller vibration frequency on tactile perception, we also fit individual psychometric functions for each participant, frequency, and condition (*frequency analysis*, 8 repetitions per intensity). These data were analyzed using a linear mixed effects model with factors controller $\times$ frequency and a random intercept coefficient for participant. Bonferroni-Holm correction was used for all multiple comparisons.

3   Results

We first investigated baseline and movement tactile thresholds independent of vibration frequency (24 responses per intensity). Figure 2 plots individual and averaged detection thresholds for the movement and baseline conditions for the Vive (left) and Index controller (middle). Average thresholds were larger in the movement compared to baseline condition for both controllers (Vive: $t_{17} = 3.25$, $p = 0.002$, $d = 0.77$; Index: $t_{17} = 4.17$, $p < .001$, $d = 0.98$), indicating that participants experienced tactile suppression. Baseline thresholds were greater in the Index compared to the Vive controller ($W_{17} = 137$, $p = 0.024$, $r = 0.60$).

For a more direct comparison of tactile suppression effects, threshold difference values for each controller type are shown in Fig. 2 (right). Suppression magnitude was not significantly different between both controllers ($t_{17} = 0.13$, $p = 0.90$). Moreover, individual threshold differences for both devices were strongly correlated ($r = 0.82$, $R^2 = 0.67$, $F_{16,1} = 32.7$, $p < .001$), suggesting similar individual levels of suppression regardless of controller type.

Results for the frequency analysis are shown in Fig. 3, plotting the data similar to Fig. 2 but when fit separately for each vibration frequency (8 responses per intensity). Here, baseline thresholds differed significantly between controllers ($F_{85,2} = 11.8$, $p < .001$, $\eta_p^2 = .20$) and frequencies ($F_{85,1} = 19.7$, $p < .001$, $\eta_p^2 = .18$). In post-hoc tests, 400 Hz had higher thresholds than both 100 Hz ($t_{85} = -3.86$, $p < .001$, $\eta_p^2 = .19$) and 250 Hz ($t_{85} = -4.49$, $p < .001$, $\eta_p^2 = .18$), but 100 Hz and 250 Hz did not differ significantly ($t_{85} = 0.64$, $p = 0.526$). Threshold differences per frequency (Fig. 3, right) all indicate tactile suppression (all
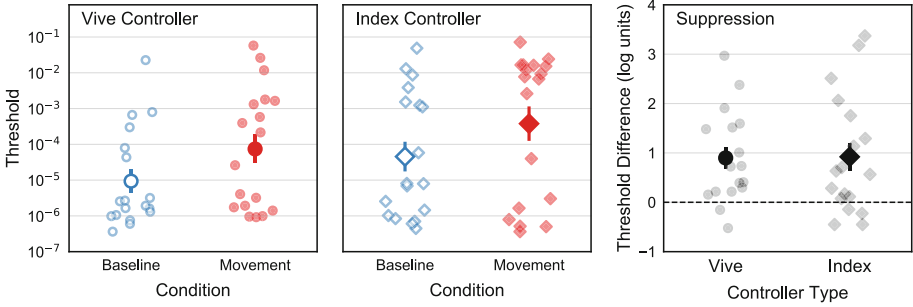
Fig. 2. *Left, Middle*: Detection thresholds in the baseline (blue, open markers) and movement condition (red, filled markers) for the two tested controller types. Functions were fit independent of frequency (24 responses per intensity). *Right*: Threshold differences (movement - baseline) for each controller. Values above zero (dashed line) indicate tactile suppression. Error bars show ±1 SEM. (Color figure online)
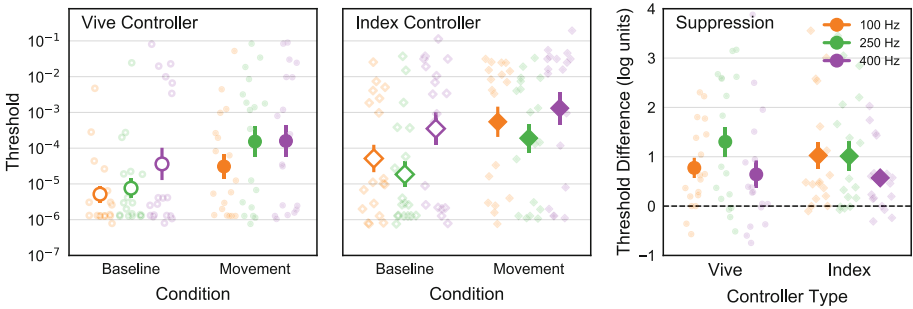

Fig. 3. *Left, Middle*: Thresholds in the baseline (open markers) and movement condition (filled markers) for each controller type, fit separately for each tested vibration frequency (8 responses per frequency × intensity). *Right*: Threshold differences for each controller and frequency. Error bars indicate ±1 SEM.

$W_{17} > 127$, all p < 0.027, all r > .52), but suppression strength significantly varied between frequencies ($F_{85,2} = 4.9$, p = 0.01, $\eta_p^2 = .08$), with the only significant post-hoc comparison between 250 and 400 Hz ($t_{85} = 3.13$, p = 0.007, $\eta_p^2 = .09$).

4   Discussion

Here, we present the first evaluation of consumer VR controllers for tactile psychophysics research. Baseline (resting) perceptual thresholds differed between controller types, indicating that devices may differ in vibrotactile presentation. Nevertheless, we found consistent tactile suppression during movement, and individual suppression was of similar magnitude and correlated between devices.

Baseline thresholds significantly differed between controllers, with the Vive controller apparently presenting the "stronger" tactile stimulus (lower threshold). This might be explained by a stronger actuator in the Vive controller or differences in actuator mounting or placement. Another explanation could relate to possible mass differences between controllers. In this case, participants would need to apply greater grip forces to hold the heavier controller, leading to stronger afferent input masking the vibrotactile stimulus. Yet, recent work does not suggest stronger suppression for greater forces [3] and mass was very similar when measured (Vive: 205 g, Index: 196 g), making this explanation unlikely. It is further unknown whether all controllers of the same type produce similar physical stimuli for a given intensity value. In any case, different controller types may be more or less suitable for perceptual threshold estimation, and care should be taken to evaluate devices before comparing results across studies, which was beyond the scope of this conference paper.

We found significant suppression during movement compared to rest in both controllers, in good agreement with previous work that found similar effects with specialized tactors [5,6,11,18,19]. The magnitude of this suppression effect was comparable for both controllers and individual threshold differences were highly correlated between devices. This suggests that we indeed measured suppression as a participant-specific variable, further supported by significant suppression effects in all tested vibration frequencies. While the fixed stimulus onset times in the baseline condition might have facilitated prediction of the stimulus and thus lower thresholds, movement-related tactile suppression is evident also with jittered baseline stimulus onset times [11]. Additionally, the larger number of trials with stimulus compared to without could have biased participants towards responding "yes" more often, but such a bias would affect all conditions equally as trial counts were identical.

The frequencies tested here predominantly activate the Pacinian corpuscles, which have a receptive range of 40–800 Hz and a peak sensitivity around 250 Hz [2,12,13]. Based on prior work, 250 Hz should therefore have the lowest baseline thresholds, with lower sensitivity and thus higher thresholds for 100 Hz and 400 Hz [2,14]. In the Index controller, baseline and movement thresholds indeed generally follow this pattern. In the Vive controller, thresholds increased with frequency, with 100 Hz being the most detectable. This might be explained by hardware differences as well, e.g. higher force at 100 Hz for the Vive actuator or resonance with the controller case. Future work could investigate the force output of each controller at different frequencies. Nonetheless, the 250 Hz widely used in prior work (e.g., [11,18,19]) appear to work well for the tested devices.

These findings also open up questions for future work. Notably, the lowest intensity tested in this study was 10^{-5}, yet quite a few participants had estimated thresholds below this level (cf. Fig. 2), indicating that they perceived some or all stimuli at the lowest level(s) presented. True thresholds thus might lie even lower for some participants. Another possibility is that steps in intensity near the lower end of the tested range might produce only little difference in the physical stimulus amplitude, or that the range of stimuli produced by the controller is

limited by hardware capabilities. To address these questions, we are currently examining the physical stimulus produced across a large range of intensities to determine a usable span of values. Notably, the suppression effects found here are unlikely to be affected by this as we compared within-subject baseline and movement thresholds. Taken together, our findings pave the way for future tactile psychophysics studies in VR using wireless, off-the-shelf hardware.

References

1. Bays, P.M., Flanagan, J.R., Wolpert, D.M.: Attenuation of self-generated tactile sensations is predictive, not postdictive. PLoS Biol. **4**(2), e28 (2006)
2. Bolanowski, S.J., Jr., Gescheider, G.A., Verrillo, R.T., Checkosky, C.M.: Four channels mediate the mechanical aspects of touch. J. Acoust. Soc. Am. **84**(5), 1680–1694 (1988)
3. Broda, M.D., Fiehler, K., Voudouris, D.: The influence of afferent input on somatosensory suppression during grasping. Sci. Rep. **10**(1), 1–11 (2020)
4. Brookes, J., Warburton, M., Alghadier, M., Mon-Williams, M., Mushtaq, F.: Studying human behavior with virtual reality: the unity experiment framework. Behav. Res. Methods **52**, 1–9 (2019)
5. Buckingham, G., Carey, D.P., Colino, F.L., Degrosbois, J., Binsted, G.: Gating of vibrotactile detection during visually guided bimanual reaches. Exp. Brain Res. **201**(3), 411–419 (2010)
6. Chapman, C.E., Beauchamp, E.: Differential controls over tactile detection in humans by motor commands and peripheral reafference. J. Neurophysiol. **96**(3), 1664–1675 (2006)
7. Chapman, C., Bushnell, M., Miron, D., Duncan, G., Lund, J.: Sensory perception during movement in man. Exp. Brain Res. **68**(3), 516–524 (1987)
8. Choi, S., Kuchenbecker, K.J.: Vibrotactile display: perception, technology, and applications. Proc. IEEE **101**(9), 2093–2104 (2012)
9. Colino, F.L., Buckingham, G., Cheng, D.T., van Donkelaar, P., Binsted, G.: Tactile gating in a reaching and grasping task. Physiol. Rep. **2**(3), e00267 (2014)
10. Fiehler, K., Brenner, E., Spering, M.: Prediction in goal-directed action. J. Vis. **19**(9), 10 (2019)
11. Gertz, H., Voudouris, D., Fiehler, K.: Reach-relevant somatosensory signals modulate tactile suppression. J. Neurophysiol. **117**(6), 2262–2268 (2017)
12. Gescheider, G.A., Wright, J.H., Verrillo, R.T.: Information-Processing Channels in the Tactile Sensory System: A Psychophysical and Physiological Analysis. Psychology press (2010)
13. Johnson, K.O., Yoshioka, T., Vega-Bermudez, F.: Tactile functions of mechanoreceptive afferents innervating the hand. J. Clin. Neurophysiol. **17**(6), 539–558 (2000)
14. Jones, L.A., Sarter, N.B.: Tactile displays: guidance for their design and application. Hum. Factors **50**(1), 90–111 (2008)
15. Manzone, D.M., Inglis, J.T., Franks, I.M., Chua, R.: Relevance-dependent modulation of tactile suppression during active, passive and pantomime reach-to-grasp movements. Behav. Brain Res. **339**, 93–105 (2018)
16. Oldfield, R.C.: The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia **9**(1), 97–113 (1971)
17. Schütt, H.H., Harmeling, S., Macke, J.H., Wichmann, F.A.: Painfree and accurate Bayesian estimation of psychometric functions for (potentially) overdispersed data. Vis. Res. **122**, 105–123 (2016)

18. Voudouris, D., Broda, M.D., Fiehler, K.: Anticipatory grasping control modulates somatosensory perception. J. Vis. **19**(5), 4 (2019)
19. Voudouris, D., Fiehler, K.: Dynamic temporal modulation of somatosensory processing during reaching. Sci. Rep. **11**(1), 1–12 (2021)
20. Wolpert, D.M., Flanagan, J.R.: Motor prediction. Curr. Biol. **11**(18), R729–R732 (2001)