Investigating Eyes-away Mid-air Typing in Virtual Reality using Squeeze haptics-based Postural Reinforcement

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ABSTRACT

In this paper, we investigate postural reinforcement haptics for mid-air typing using squeeze actuation on the wrist. We propose and validate eye-tracking based objective metrics that capture the impact of haptics on the user’s experience, which traditional performance metrics like speed and accuracy are not able to capture. To this end, we design four wrist-based haptic feedback conditions: no haptics, vibrations on keypress, squeeze+vibrations on keypress, and squeeze posture reinforcement + vibrations on keypress. We conduct a text input study with 48 participants to compare the four conditions on typing and gaze metrics. Our results show that for expert qwerty users, posture reinforcement haptics significantly benefit typing by reducing the visual attention on the keyboard by up to 44% relative to no haptics, thus enabling eyes-away behaviors.

CCS CONCEPTS

• **Human-centered computing → HCI theory, concepts and models**; *Mixed / augmented reality*; *Virtual reality*.

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1 INTRODUCTION

Freehand *qwerty* typing on a virtual keyboard floating in air is increasingly being explored for AR/VR (augmented reality, virtual reality) [10, 12, 19]. However, a virtual keyboard lacks the haptic feedback that makes physical keyboard typing an efficient and pleasant task. The physical keyboard enables touch typing where an expert user feels comfortable enough to avert their gaze away from the keyboard (*"eyes-away"*) and towards where the words are being typed. The physical keyboard’s haptic assistance can be broken down into two components: 1) Kinesthetic: the physical surfaces of the keys and the desk provides the user kinesthetic awareness of their hands relative to the keyboard and helps reinforce the appropriate hand posture. 2) Tactile: the actuation of keys provides tactile feedback upon key press.

While the work in the space of providing mid-air haptic feedback for such 10-finger *qwerty* typing is sparse, the most relevant recent work [19] investigated the tactile component and found that vibrotactile feedback on the corresponding fingers for key presses resulted in lower user effort and mental demand. However, the work found the typing performance with tactile feedback to be comparable to when tactile feedback was not provided. The paper explained this mismatch between subjective scores and typing performance by theorizing that the speeds remained similar because users tended to compensate for the lack of tactile feedback by increasing their cognitive and visual attention to the task in the absence of tactile feedback. However, beyond the user quotes, the paper did not present any objective evidence to support this explanation.

In this paper, we advance upon the above work in two major respects:

- First, we investigate the addition of squeeze feedback as a new haptic modality to convey kinesthetic feedback for postural reinforcement, as well as for keypresses.
- Second, we propose and validate eye-tracking based objective metrics that capture the impact of haptics on the user’s experience that traditional performance metrics like speed and accuracy do not.

To this end, we designed three wrist-based haptic feedback conditions: *vibrations on keypress*, *squeeze+vibrations on keypress*, and *squeeze posture reinforcement + vibrations on keypress.* We conducted a text input study with 48 participants to investigate the effects of these three haptics conditions against a baseline condition with *no haptics* on typing performance and gaze metrics. Our results show that for expert *qwerty* users, posture reinforcement haptics significantly benefited typing by reducing the visual attention on the keyboard by 44% relative to no haptics, thus enabling more eyes-away behaviors.

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2 RELATED WORK

Other than the existing work on tactile feedback for mid-air typing described in the Introduction [19], there is sparse work in the space of mid-air haptic feedback for *qwerty*-style text-input. Our discussion of related work focuses on the related threads of text entry in VR and on wrist haptics for VR.

2.1 Encumbered Text-entry in VR

Encumbered encompasses techniques where the user interacts with externally grounded devices, such as a physical keyboard, as well as techniques where the user's hands are significantly encumbered by controllers or other devices. Current commercial VR devices use controllers for text-entry where a ray cast from the controllers is used to select keys on a *qwerty* keyboard [20, 46]. Prior work has investigated dedicated handheld devices for VR typing such as Twiddler [6], 9-key keypads [14], smartphones [23], and bimanual touchpads with hover detection [43]. Speicher et al. [44] evaluated multiple techniques based on current commercial controllers including raycasted pointing, direct tapping, controller as gamepad, and found raycasted pointing as the fastest with 15.4 words-per-minute (WPM). Other studies have investigated *non-qwerty* layouts with controllers including circular [14, 51] and cubic [49] layouts. Multiple glove-based or optical tracking-based techniques have been proposed that map a keyboard layout on to the hand/fingers [14, 21, 33, 39], reporting speeds in the range of 5–10 WPM.

The work on physical keyboards in VR can be classified into one of two categories: variations in visual feedback based on tracking hand-finger motion in the real world [5, 16, 22, 28] and variations in hand representations [15, 24, 32]. Most studies in this category report typing speeds in the range of 25–45 WPM, which are much higher than other alternatives in VR. This lends credence to our approach of investigating 10-finger typing in VR and whether tactile feedback can help mitigate the problems arising from lack of tangibility in air. For a detailed review of physical keyboards in VR (and VR text-entry in general), we refer the reader to Dube et al. [9].

2.2 Freehand *qwerty* Text-entry in VR

Freehand refers to unencumbered techniques that specifically focus on *qwerty* keyboard typing using hand tracking. In 2003, ARKB [27] used vision-based tracking of fingertips for multi-finger typing on a virtual *qwerty* keyboard. Markussen et al. [30] showed that a single-finger mid-air vertical keyboard on a large display yields a speed of 13.2 WPM in its final session, after $\sim$ 75 mins of practice. VISAR [11] uses word-level decoding for a single-finger mid-air vertical keyboard in VR yielding 17.8 WPM after $\sim$ 90 minutes of practice. ATK [50] uses Leap Motion to implement a 10-finger mid-air horizontal *qwerty* keyboard supported by a word-level decoder and reports speeds of 29.2 WPM for a limited vocabulary phrase-set after $\sim$ 1 hour of practice. None of these works examined the influence of haptic feedback on typing performance. Dudley et al. [10] investigate the differences in on-surface vs. mid-air *qwerty* keyboard typing in VR and conclude that when using a Wizard of Oz decoder, the performance of 10-finger on-surface typing (51.6 WPM) is higher than mid-air (34.5 WPM). Wu et al. [47] propose a glove that provides vibration feedback on the fingertips for a mid-air *qwerty* keyboard. However, they do not investigate typing performance.

Even though the performance reported in prior work is specific to their study design, physical keyboard style text-entry appears to be one of the most promising techniques for performant typing in VR. It is freehand, has potentially high speeds, and resembles physical keyboard typing.

2.3 Wrist Haptics: Vibrations and Squeeze

While there have been multiple works on mid-air haptics pertaining to gloves (see [34] for a review) and controllers (see [42] for a review), we focus our attention on wrist haptics. Several works have explored placing multiple vibrotactors on the wrist [7, 8, 18, 31]. Matscheko et al. [31] concluded that placing tactors around the wrist circumference was best. Carcedo et al. [7] found that users can reliably detect five vibration motors around the wrist.

Squeeze feedback on the wrist has recently received particular interest in the literature. Pohl et al. [38] used pneumatic actuation to create uniform compression around the wrist. Zhu et al. [52] built a pneumatically actuated sleeve that enabled vibrations, squeeze, and skin stretch. Gupta et al. [17] used shape-memory alloy springs to overcome size constraints of pneumatic actuation. Pezent et al. [37] built Tasbi that delivers squeeze using a mechanical string retraction mechanism and also consists of six vibrotactors. In this paper, we use the Tasbi device for our investigation.

A related area of work here is haptics guidance which has been used for motor learning, teleoperation, rehabilitation use cases. This a huge area of work with applications in multiple engineering and medical disciplines. Please refer to [2, 4, 26] for surveys of prior work in the field.

3 HAPTIC DESIGN

Wrist-worn haptics enables the user to receive haptic feedback close to the hand while leaving the hands free for interactions. Haptic components on the fingers may also interfere with the hand tracking driven by headset-based cameras. Prior work on vibrotactile feedback on fingers [19] used fiducial markers for hand tracking. In this paper, we focus on wrist-worn haptic feedback and use the native hand tracking in the Quest VR headset.

While vibrations are good at providing short-term feedback, the sensations can become annoying if played continuously for a long time. Wrist squeeze feedback at the appropriate strength, on the other hand, can be applied continuously and enables sensations that are useful for making multisensory experiences with virtual objects in VR more believeable [37].

To design our haptic feedback conditions, we used the Tasbi wristband device [37] which enables a wide range of squeeze force and includes six vibrotactile motors around the band. We prototyped various haptic designs consisting of different combinations of squeeze and vibrations towards invoking the kinesthetic and tactile components of a typing interaction. We finalized the following three haptic condition designs, and a baseline condition with no haptics, for our study:

3.0.1 *No haptics (NH).*

This condition consisted of no haptic feedback. Participants received visual feedback upon key collision (key

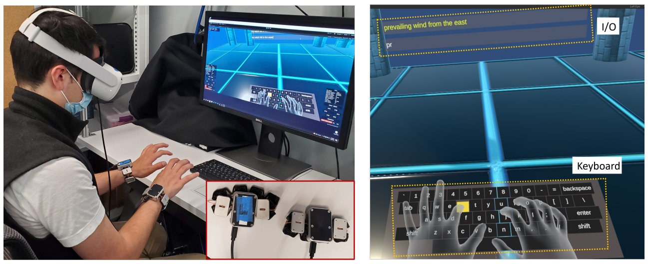

Figure 1: (left) Apparatus consisting of the Quest2 VR headset with a Tobii eye tracker inside, and Tasbi squeeze+vibration wristbands on both hands. (right) Virtual keyboard in VR

turns lighter) and keypress (key turns yellow). Note that the keypress is only registered when the key is pressed up to a certain predefined depth (0.9cm). If the user collides with a key, but does not press it all the way, then it is considered a key collision. Overall, the virtual keyboard design Fig 1 adhered close to the virtual keyboard in prior work [19].

3.0.2 Spatial Wrist Vibration on Keypress (VK). This condition presented vibration feedback for key surface contact and key press events. Each finger was mapped to an individual vibration actuator in the haptic bracelet (see Section 4.2). The vibration feedback consisted of a 100 ms decaying sinusoidal signal starting with the collision of the finger on the key surface until the keypress. Previous research has successfully used decaying sinusoids to approximate contact transients, e.g., a finger tapping a surface [25]. For surface contact the frequency was set to 300 Hz, and for the keypress event the frequency was 150 Hz (in the optimum region for the vibration actuators). If a user stops a fingertip at the location where the key collision event occurs, the decaying sinusoidal still completes its 100ms feedback. Same applies if a user presses a key slowly. We made this choice since based on our observation of mid-air typing dynamics, such cases occurred very infrequently and we therefore erred on the side of making the keypress feel good when it is performed as expected. The lower frequency content for the keypress event produces the sensation of a less rigid surface interaction, getting closer to the sensation of a displacing key.

3.0.3 Squeeze + Spatial Wrist Vibration on Keypress (SVK). This condition extended the VK condition (ii) with squeeze feedback that was proportional to key displacement. As users collided with a key and progressed towards a keypress, squeeze increased linearly through the key's range of travel from 0 to MAXSQUEEZE (described later). Thus, squeeze served as a substitute for the spring forces once would feel when pressing real keys and was similar to the mid-air button concept presented in [37]. If multiple fingers were in simultaneous contact, the total amount of wrist squeeze was the sum across all contributing fingers (with an upper bound). The spatial wrist vibration on contact was identical to the one used in VK. Note that the squeeze feedback here is meant to provide the feeling of a key in addition to the vibration feedback in VK.

3.0.4 Squeeze for Posture Reinforcement + Spatial Wrist Vibration on Keypress (SPVK). This condition extended the VK condition (ii) with squeeze feedback that was inversely proportional to the distance between the user's wrist location and a pre-determined optimal wrist location. Squeeze was at its highest value when users were at the optimal location, and decreased as their wrists drifted away from this location. The optimal location was set based on the wrist center point being in the position such that the index fingers rested on f and j keys. The following equation determined the squeeze strength S for a distance D (in meters) of the wrist from the optimal location:

$$S = \frac{MAX\_SQUEEZE}{(1+D)^{300*D}} \tag{1}$$

This was obtained based on iterative prototyping and ensured an initially slow, but subsequently rapid reduction in squeeze strength as distance increases. Thus, SPVK provided a sustained reinforcement stimuli when users were in the correct posture and tried to invoke the feedback of resting one's wrists on a physical surface as is typical for typing. Our hypothesis is that posture reinforcement will enable the users to be more comfortable in averting their gaze away from their keyboard since they can be more confident about the position of their hands and fingers in space.

3.1 Posture Reinforcement vs. Posture Correction

We also considered providing posture correction feedback where the squeeze increases as the wrist's distance from its optimal location increases. We conducted a pilot with four users to compare reinforcement vs. correction and found that 3 out of 4 users preferred posture reinforcement since it was more analogous to the physical keyboard.

Note that we don't have a squeeze condition without vibrations. Since squeeze actuation has higher bulk and power needs, we wanted to focus on the *incremental* significance of squeeze in addition to vibration feedback on the wrist.

4 USER STUDY: EFFECT OF HAPTIC FEEDBACK ON MID-AIR TYPING PERFORMANCE AND GAZE BEHAVIOR

4.1 Participants

48 participants (22 female, 22 male, 2 non-binary and 2 preferred not to say, age range: 22-65, mean: 39, 3 left handed and 1 ambidextrous) did the study. Ten of them had a prior experience with VR, but none of them were habitual users.

4.2 Apparatus

Participants did the study in virtual reality wearing the Quest 2 VR headset. We fitted a Tobii eye tracker inside the headset to provide eye tracking data. Quest 2's native library was used for hand tracking. The Tasbi haptic bracelet [35] was used as the haptic apparatus for this study. The bracelet was capable of rendering both vibration and squeeze stimuli. Vibration stimuli were rendered via six linear resonant actuators (LRA) (MPlus 1040W, f_0 = 170 Hz) spaced evenly around the circumference of the wrist. Vibration patterns were authored using the Syntacts framework [36]. Squeeze stimuli were rendered using a cord tensioning mechanism capable of delivering between 1 N and 12 N of uniform squeeze force. The amount of squeeze stimuli rendered was controlled for using incremental encoder feedback and closed-loop position control on the cord tensioning mechanism. Two bracelets were worn by participants, one on each wrist (see Fig. 1), and were tethered to the primary desktop through Quanser Q8-USB and MOTU 24 AO hardware interfaces. Prior to beginning the experiment, the Tasbis were calibrated to participants' wrists so that the initial fit was comfortable and so that a consistent range of squeeze stimuli would be rendered across all subjects. The calibration procedure has been previously described in [37] and [35]. The magnitude of the vibrotactile stimuli were not calibrated. Only the squeeze feedback was calibrated.

4.3 Study Design

Typing on the mid-air virtual keyboard is an unfamiliar experience and the asymmetric learning effects can be too high for counterbalancing to overcome [19]. We thus adopted a between-subjects design with 12 participants each in four conditions (*NH*, *VK*, *SVK*, and *SPVK*). All participants wore the wristband to keep the encumbrance constant. We recorded participants' physical keyboard typing speeds using an online test [45].

One of our hypotheses is that haptics will benefit expert *qwerty* typists more than novices. This is because even on a physical keyboard, novice typists aren't able to take their eyes away from the keyboard as much as more expert users. Without haptics, novices and experts will have to pay similar attention to the keyboard and their key presses. We therefore split the participant set based on the physical typing median value, <47.5 WPM ("novices") and >47.5 WPM ("experts"). Each of the four conditions had 6 novices and 6 experts. The *novice* and *expert* nomenclature in this case, while not entirely accurate, allows us a suitable enough distinction to test out the differentiating impact of haptics on novice and expert *qwerty* users.

To capture the impact of haptics over time, each participant did 4 blocks of typing. Each block consisted of 5 phrases sourced from the standard MacKenzie phrase-set [29], for a total of 20 phrases per participant. We believe that the benefit of haptics will increase as users' get more practice on the mid-air keyboard. Typing on the mid-air virtual keyboard is an unfamiliar experience and involves learning to deal with issues such as coactivation due to the lack of the physical resistance of the keys [10]. Thus, the user will need some time to get familiar with mid-air typing with their full attention before they can start using haptics to lower their attention. However, building sufficient familiarity with the keyboard can take longer than a single study session. We therefore enabled a speed up the learning process by using the same 5 phrases for all 4 blocks. This allowed the user to get quickly climb their learning curve for those phrases without making the study too long.

4.4 Procedure

Participants sat on a chair and first wore the band and the headset. We then calibrated the eye tracker. We did not collect data for participants whose eye tracking results were below the required eye tracking accuracy threshold. After calibrating the eye tracker for each user, the eye tracking error was determined based on the average gaze deviations of 5 targets. If the avg. deviation from the centre of the targets was higher than half the size of the target (which was same as size of key), the participant was removed. We removed two participants based on this criteria. The final participant set *after* removing such participants is the balanced 12 participants ×4 conditions = 48 participant set reported above. They were then asked to place their hands in a comfortable position as if to type on a horizontal keyboard in air while keeping their shoulders completely relaxed and their elbows on the armrest so as not to fatigue their arms. The virtual keyboard was then placed under their fingers and adjusted according to their preference. Participants were then asked to complete two practice phrases on the keyboard without any feedback to get familiar with the typing interface. Participants were explicitly instructed on the keyboard design and that they were free to use as many fingers as they want to use. In keeping with prior unconstrained text-entry evaluations, participants were instructed to type as quickly and accurately as possible, and that they could correct errors (using *Backspace*) they noticed immediately, but could also choose to ignore errors which they notice after a few characters have been typed. Participants were then explained the haptic feedback condition and were asked to try it out for a random phrase. They then started the first block. Pressing *Enter* took them to the next phrase. To prevent inadvertent *Enter* presses, the press was only registered if the minimum string edit distance (MSD) of the transcribed phrase from the stimulus phrase was < 8. Participants were given a 2 min break between blocks. Participants did a post-study preference and NASA-TLX questionnaire. The participant responses were not under observation during this time to minimize response bias.

4.5 Measures

We measured *Speed* and *Uncorrected Error Rate (UER)* using standard metrics [3]. Speed is measured in words-per-minute: $WPM = ((|T| - 1) \times 60)/(S \times 5)$ where |T| is the transcribed phrase length and S is the time starting from the first key press until the last key press before *Enter* including time spent in correcting errors. UER represents the rate of errors that were not corrected by the user (referred to as incorrect not fixed in [3]). $UER = MSD(P, T) \times 100/max(|P|, |T|)$ where P is the stimulus phrase. We further analyzed other typing micro-metrics, subjective scores, and gaze behavioral metrics that we discuss in the relevant subsections.

5 RESULTS

We measured the effect of three different haptic conditions (VK, SVK and SPVK) against the baseline condition (NH) using a between-subjects study design (N = 48 participants).

5.1 Speed and accuracy did not differ among haptic conditions

First, we investigated the effect of different haptic conditions on the speed and the error rate of typing in VR. We calculated the aggregate VR typing speed for all four blocks for each of the three haptic conditions (VK, SVK and SPVK) and the NH baseline condition. Consistent with prior reports [19], VR typing speed was not affected by presence or absence of haptic feedback (one-way ANOVA $F(3, 44) = 0.67; p = 0.57, \eta^2 = 0.04$, Fig 2A). However, there was a practice effect after consistent use of haptics over time. Participants' VR typing speed significantly improved for all conditions (including NH baseline condition) after four blocks (NH:

$F = 5.71 p < .01$, rmANOVA for all blocks; $p < .01$ pairwise Tukey test between first and the last blocks; VK: $F = 2.97, p < .05$, rmANOVA ; $p < .01$ pairwise Tukey test; SVK and SPVK: $F = 11.29$ and $F = 8.32, p < .001$, rmANOVA; $p < .001$ pairwise Tukey test; Fig 2B). Nevertheless, the VR typing speed in the last block for any of the haptic conditions was still not significantly different from the NH baseline condition in the last block (one-way ANOVA $F(3, 44) = 1.52; p = 0.22, \eta^2 = 0.09$, Fig 2C).

Furthermore, the uncorrected error rate of typing in VR (UER) for any of the haptics conditions also did not differ significantly from the NH baseline for aggregate over all the blocks (one-way ANOVA $F(3, 44) = 2.17; p = 0.10, \eta^2 = 0.13$, Fig 3A) or for the last block alone (one-way ANOVA $F(3, 44) = 2.28; p = 0.09, \eta^2 = 0.13$, Fig 3C). We did not observe a significant improvement in error rate with practice Fig 3B, unlike improvement in speed.

As seen in Fig 2B, the mean speeds for all four haptic conditions start out at very similar values, with the lines diverging over the course of the blocks. While they do not diverge enough to be significantly different as far as speeds are concerned, we observe the trend in our subsequent metrics as we had earlier speculated in section 3.1. Therefore, we will only discuss the analysis of the last block henceforth.

5.2 Key Collisions reduced in SVK

Apart from speed and accuracy, we measured other typing micro-metrics such as key collisions per character (a user may perform multiple incorrect key collisions when trying to hit a key due to the coactivation problem [10]), and time between consecutive key presses to gain further insight on the effect of haptics on mid-air VR typing.

Participants had significantly lower key collisions per key during the SVK condition, relative to the baseline NH condition ($p < .05$ t-test, Fig 4A). This is interesting since this indicates that the additional squeeze feedback on key press indeed helped the user avoid unintended collisions.

The time between presses was not different for any of the haptic conditions(one-way ANOVA $F(3, 44) = 1.02; p = 0.39, \eta^2 = 0.06$, Fig 4B).

5.3 Effect of haptics on gaze behavior metrics

As prior work suggests [19], users might compensate for the lack of haptic feedback by increasing their visual attention. Further, participants' spatial and temporal gaze patterns along with gaze metrics are strong correlates of cognitive and motor processes such as visual attention [13], motor preparation and execution [41], decision making [40], and performance monitoring [1] and therefore, gaze behavior is a valuable modality for investigating implicit user behaviors. We thus come up with the following four hypotheses on the effect of haptics, each pertaining to a different gaze behavior:

- H1: Users will spend less time looking at the keyboard when there's haptic feedback than without haptics. Haptics will help users confirm their keypresses and determine the position of their hand with respect to the keyboard layout.
- H2: With haptic feedback, users' gaze will spend less time aligned with their finger or with the next key they are about to press. Users will feel more comfortable not following their finger or eyeing the next key when there's haptics present.
- H3: With haptic feedback, users will switch their gaze less frequently between the i/o prompt and the keyboard.
- H4: With haptic feedback, whenever users' gaze falls over the keyboard, it will be able to scan the keyboard faster.

5.3.1 *Time spent looking at the keyboard.*

First, we assessed the amount of time the participants spent looking at the keyboard (Figure 1) while typing in VR (again, the analysis is for the last block). Consistent with this hypothesis, the participants spent 14.5% and 7.8% less time looking at the keyboard for the VK and SVK conditions respectively, relative to the NH baseline condition. The difference however is not statistically significant. The effect of SPVK is statistically significant where participants spent 23% less time looking at the keyboard relative to the NH baseline condition ($p < .05$ t-test, Fig 5A).

Furthermore, we found that the amount of time participants spent looking at the keyboard while typing in VR varied inversely with their typing speed on a physical *qwerty* keyboard (expertise with the *qwerty* layout). This was specifically true for the SPVK condition (Fig 5B; Regression model: $y = -0.59x + 73.2$, where y is amount of time looking at the VR keyboard while typing and x is the typing speed in the physical keyboard. The overall regression was statistically significant $p < .05$; Pearson $r : -0.65$). As previously mentioned, if a participant were not familiar with the *qwerty* layout and has limited expertise typing on a physical keyboard, their level of expertise typing in VR even with haptics would still be expected to be limited. Haptics should therefore benefit expert *qwerty* typists more.

To validate our reasoning, we analyzed gaze behaviors for novices and experts separately (See the Appendix for speed and accuracy graphs for novices and experts). As mentioned earlier, the novice-expert separation was based on users' physical keyboard typing speeds (Fig 6A). Novice typists' looking behavior during the haptics conditions was not very different from that of the NH baseline condition (Fig 6B). In fact, with VK and SVK conditions, they looked 13%, and 2% less at the keyboard, relative to the NH baseline. For expert typists, with VK and SVK conditions, participants looked 15.33% and 13.02% less at the keyboard, relative to the NH baseline condition. None of these were statistically significant, however. The SPVK condition was statistically significantly different though, with a huge 44.1% significant reduction in the time spent looking at the keyboard relative to the NH baseline condition ($p < .01$, t-test; Fig 6C).

It is also worth noting that the experts adapted to SPVK condition, over four blocks, much faster than the novice participants ($F = 3.25, p < .05$, rmANOVA and $p < .01$ post-hoc Tukey test, Fig 7).

Together, these results suggest that with SPVK condition, the expert participants spent significantly less time on the keyboard, enabling more eyes-away typing behavior during mid-air VR typing, validating H1.

5.3.2 *Angular distance between the gaze ray and the finger or next key.*

To test H2, we calculated the extent of eye-hand disassociation by measuring the angular distance between the gaze ray and the finger / next key. We found that expert participants had 27% higher

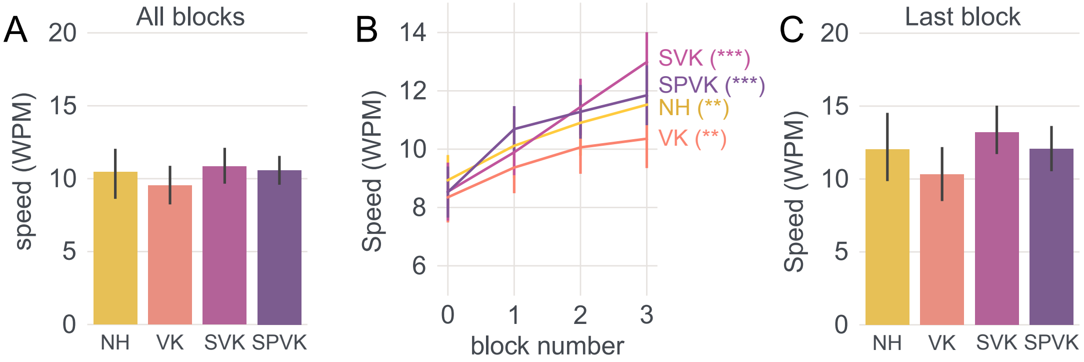

Figure 2: A) Speed of typing across all blocks, all participants. B) Speed of typing by block across all participants. Pairwise post-hoc tukey test results (after an rm-ANOVA) between the first and the last block for each conditions is shown at the right. $***$ means $p < .001$, $**$ means $p < .01$. C) Speed of typing for last block only, across all participants.

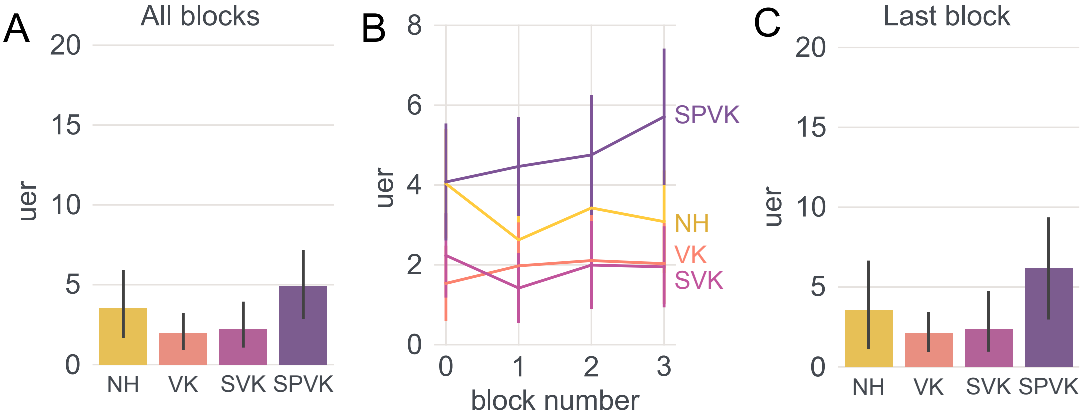

Figure 3: A) Uncorrected Error Rate (UER) across all blocks and all participants. B) UER for each block across all participants. C) UER for last block only, across all participants.

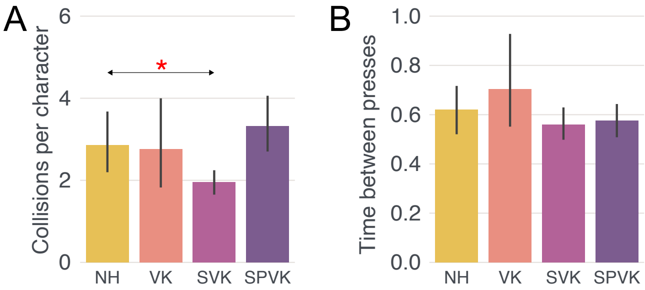

Figure 4: A) Collisions per character B) Time between presses. $*$ means $p < .05$.

eye-hand dissociation for SPVK condition relative to the baseline, but the difference was not significant ($P = .19$, t-test, Fig 8A).

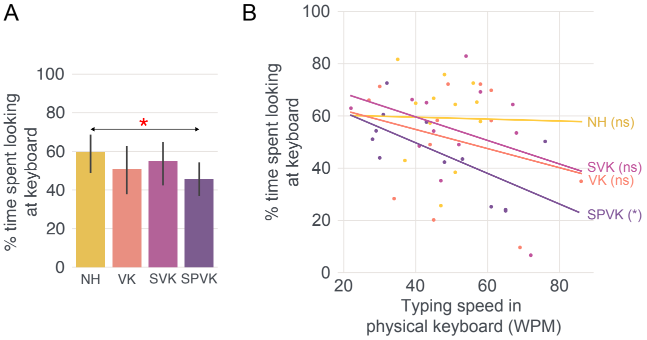

Figure 5: A) Proportion of time participants spent looking at the keyboard during typing. B) Dot plot of the proportion of time each participant spent looking at the keyboard by typing speed, along with regression lines. $*$ means $p < .05$. Error bars are 95% CI

5.3.3 Gaze Location Switching. To test H3, we calculated the number of times the participants switched back and forth, normalized by duration, between the i/o prompts and the keyboard while typing (Figure 1). We found that the expert participants made 52%

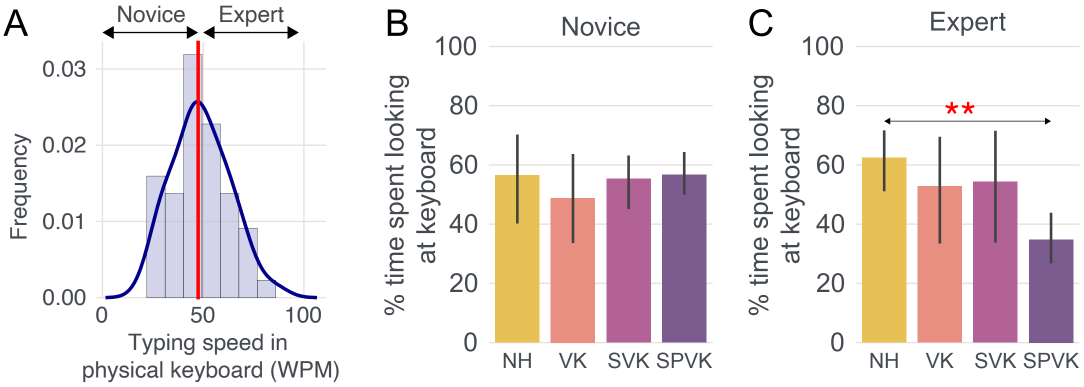

Figure 6: A) Distribution of typing speed in physical keyboard for all participants. The participants were split into novice and expert based on the median split (vertical red line) at 47.5 WPM. B) Proportion of time novice participants spent looking at the keyboard during typing for each of the three haptic conditions and the NH baseline condition. C) same as B but for expert participants. ∗∗ means $p < .01$. Error bars are 95% CI.

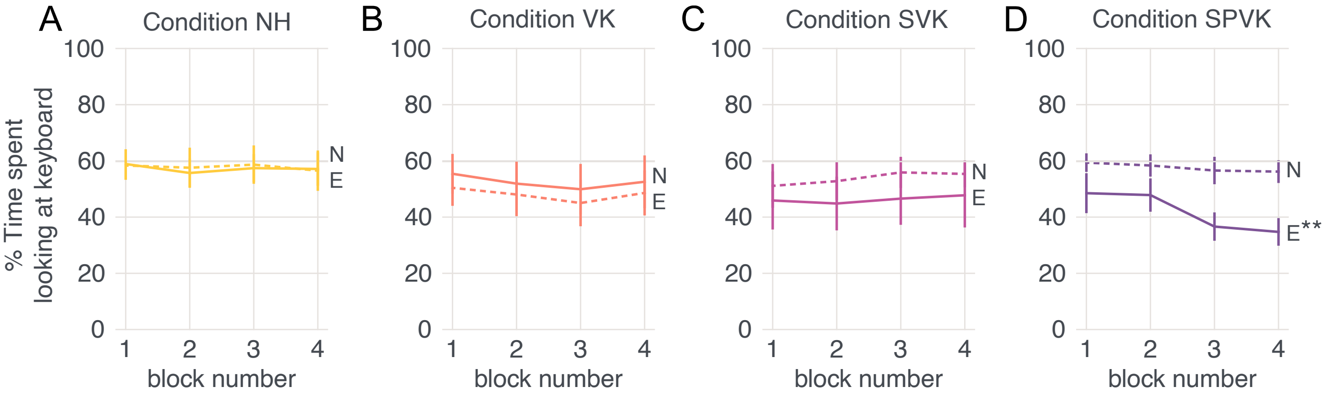

Figure 7: Proportion of time novice (broken line) and expert (solid line) participants spent looking at the keyboard during NH (A), VK (B), SVK (C) SPVK (D) conditions for each of the four blocks. ∗∗ means $p < .01$.

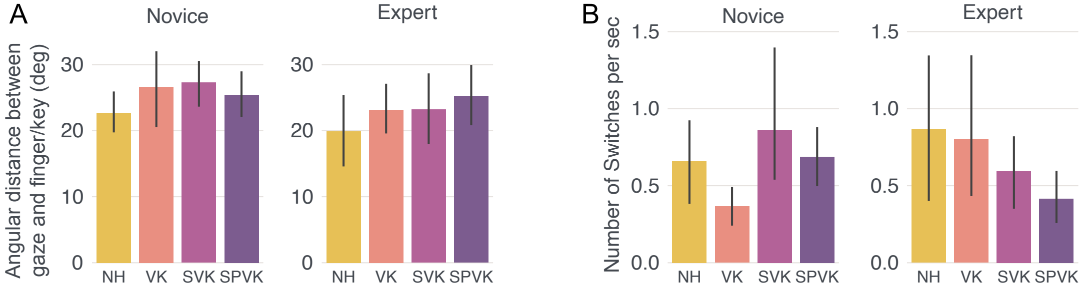

Figure 8: A) Angular distance between the gaze and the finger/ next key for novice (left) and expert (right) participants during typing for each of the three haptic conditions and the NH baseline condition. B) Same as A but for number of gaze switches per second.

fewer back and forth gaze switches between the i/o prompts and the keyboard while typing with SPVK conditions ($p = .14$ t-test, Fig 8B).

5.3.4 Gaze Velocity. Finally, we measured participants' normalized gaze velocity while they looked at the keyboard and typed. Higher gaze velocity indicates that whenever the participants' gaze falls on the keyboard, they are able to scan the keyboard more quickly.

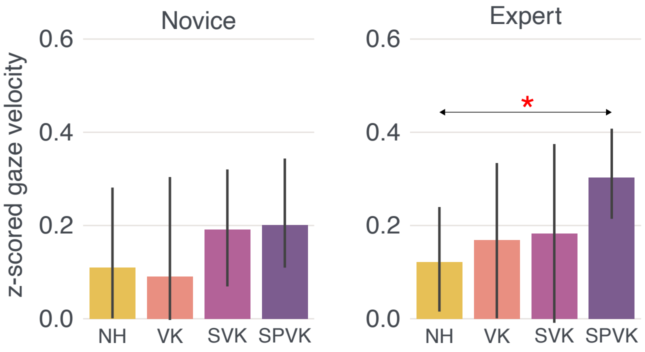

Figure 9: Z-scored gaze velocity while participants looked at the keyboard during typing for novice (left) and expert (right) participants. $*$ means $p < .05$. Error bars are 95% CI

Expert participants had significantly higher gaze velocity in the SPVK condition compared to the NH baseline ($p < .05$ t-test, Fig 9), validating H4.

5.4 Subjective scores

While subjective scores in between-participant studies are subject to uncertainty due to the variation in how different participants interpret the scale, we report the scores here. Expert participants reported significantly lower physical demand with haptics than the baseline NH condition ($p < .01$) (Fig 10). This suggests that haptic feedback has a meaningful impact on the experience of expert users.

6 DISCUSSION

Here we first summarize our key findings and then discuss their impact and future work.

First, SPVK benefited the participants the most especially in terms of lowering the need for visually attention as demonstrated by the 44% reduction in the time spent looking at the keyboard by experts as well as in the angular distance, gaze switching, and gaze velocity metrics (Fig 5, 6, Fig 8A, Fig 8B, Fig 9). This shows that the kinesthetic posture reinforcement component of physical typing can indeed be provided to a certain extent using squeeze in this manner. P37: *"I felt that the squeeze for reinforcement helped you stay in the right position to press the keys most accurately."*

Second, VK and SVK showed lower visual attention in the gaze metrics, but the differences were not statistically significant. However, SVK resulted in fewer collisions while mid-air typing. This indicates that the additional squeeze feedback on key press helped the user avoid unintended collisions.

Third, haptics benefited expert *qwerty* typists more than novices (Fig 6, 10). Even on a physical keyboard, novice typists aren't able to take their eyes away from the keyboard as much as experts. Without haptics, novices and experts paid similar attention to the keyboard and their key presses. As the fidelity of haptic feedback increases, users hewed closer to their physical behaviors, which meant that expert typists benefited from the haptic feedback more than novices. Furthermore, although more practice with haptics (specifically, SPVK condition) promoted eyes-away behavior in expert users, it also led to slight but non-significant increase in UER. This could be because of the speed-accuracy trade-off [48]. That is, with more practice, haptics improved users' typing speed, since it gets less attentionally and physically demanding, while potentially compromising typing accuracy.

Finally, the benefit of haptics increased as users got more practice on the mid-air keyboard (Fig 7). This confirms our assumption that users needed some time to get familiar with mid-air typing with their full attention before they could start using haptics to lower their attention. Although we see trends in speed, accuracy and gaze metrics with more practice, they did not stabilize during the 4 blocks we studied here. We expect the trends to stabilize over a few additional blocks and thus a future study to evaluate longer time effects of haptics would be highly informative.

6.1 Comparison of different haptics conditions

Here we studied the effects of three haptic conditions (VK, SVK and SPVK) on user performance. Since any wrist device will probably include vibrotactiles already, here, our purpose was to find the incremental value of squeeze in addition to vibrotactile feedback. We suspect that incremental value of adding a feedback such as squeeze for interaction would be one of the important questions while developing a consumer device and we believe our findings can inform such decisions.

Further, both VK and SVK have comparable speed and error rates since the differences are non significant. Therefore, we can't definitively say much about the speed accuracy comparisons between them. SPVK in this respect provides a significant improvement.

6.2 Impact of Haptics: Participant Variations

The difference in novice and expert typists can be explained from the physical keyboard behaviors. If a novice user can't take their eyes away from a physical keyboard, they won't be able to do so with mid-air haptics regardless of how good it may be.

We observe that there are multiple metrics in our results where the means appear to be quite lower or higher, but do not end up being significant. While this may partially be due to the number of participants, it also indicates inter-participant variability even after splitting novice and experts. While some participants found the feedback to be useful, some did not like the vibration or squeeze sensations and tried to ignore them. Thus there's a component of individual preference to the impact of haptics beyond just the task (typing) expertise. The effect of SPVK is strong enough to overcome this variability for certain metrics, but that is not the case for VK and SVK. While there may be a multitude of reasons behind a user preferring haptic feedback or not, one way we can improve this in our system is to personalize the squeeze and vibration ranges based on the user's perceptual sensitivity and comfort. While we calibrated the wristband for each participant's wrist size, some participants did report a feeling of discomfort over time. Personalization for individual sensitivity can make the feedback more pleasant and make the user more amenable to use the information conveyed by it.

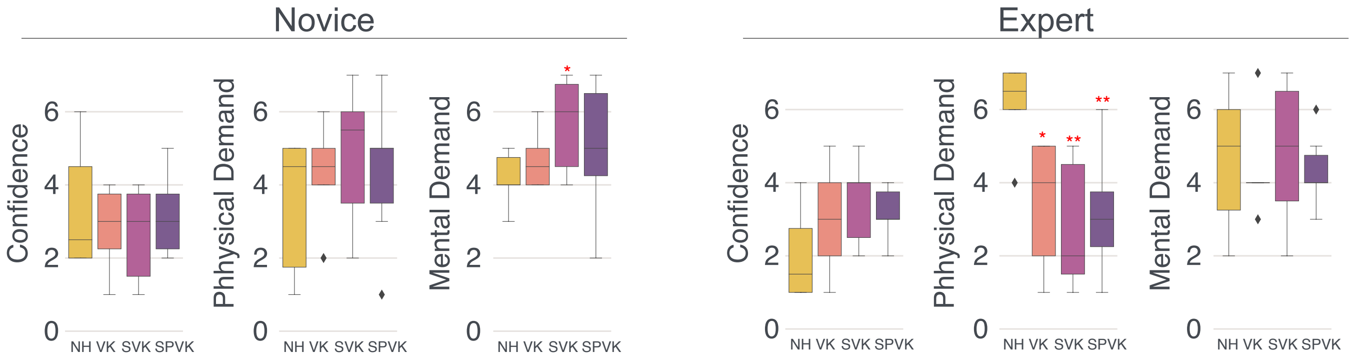

Figure 10: Participant subjective score box plots for confidence, physical demand and mental demand for novice (left) and experts (right). $*$ means $p < .05$ and $**$ means $p < .01$.

6.3 Gaze Metrics as Objective Evidence for the Impact of Haptics

This paper provides evidence of the utility of using gaze behavioral metrics as objective measures of the impact of haptics on user interactions. This is especially true in scenarios where the impact of haptics is not captured in the traditional task performance metrics, but is subjectively *felt* when using it. Gaze metrics can thus help product designers weigh pros and cons of including different haptic capabilities in future devices more empirically. While some our metrics are specific to typing, others such as gaze velocity and angular distance can potentially be adapted for use in other interactions such as grabbing, pointing, manipulation etc.

6.4 Posture Reinforcement Haptics for Eyes-away Interactions

Providing physical resistance haptics in mid-air akin to physical objects is a hard problem. A crucial outcome of physical resistance is that the user's hand is inherently holds its place relative to that object. Thus posture reinforcement haptics even without physical resistance, as we demonstrate, can be useful in providing this piece of information to the user helping them maintain their hand posture. It is crucial however for such feedback to be not annoying over long durations. Future work in this space can explore other haptic modalities such as pneumatic and glove approaches which may be able to provide even more nuanced forms of reinforcement.

7 CONCLUSION

Our work is the first investigation of the value of remote wrist posture reinforcement haptic feedback for mid-air text input in VR . Our results suggest that while haptic feedback does not result in significant improvements in user speed and accuracy, posture reinforcement haptics resulted in a significant difference in terms of their visual attention on the keyboard. One potential reason for this trend is that in the absence of haptic feedback users use their visual and cognitive attention more, thus maintaining the same performance but expending more effort. This shows that the value of haptic feedback needs to be measured by going beyond traditional performance metrics. Our work conclusively demonstrates the use of gaze metrics as objective evidence for the impact of haptics in the task. We believe haptic feedback is a crucial component for text-input in VR and hope that our work on posture reinforcement feedback and on gaze metrics serves as a guide and impetus for researchers and product designers.

ACKNOWLEDGMENTS

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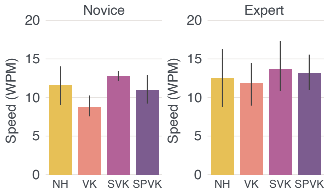

Figure A1: Speed of typing (in WPM) for the last block for novice and expert participants.

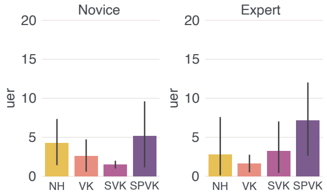

Figure A2: UER for the last block for novice and expert participants.