Exploring Virtual Keyboard Position in Mixed Reality

Joshua Reynolds
Computer Science
Michigan Technological University
Houghton, Michigan, USA
joshuare@mtu.edu

Scott A. Kuhl
Computer Science
Michigan Technological University
Houghton, Michigan, USA
kuhl@mtu.edu

Keith Vertanen
Computer Science
Michigan Technological University
Houghton, Michigan, USA
vertanen@mtu.edu

Abstract

Entering text on a mixed reality headset while on the go is often performed by typing on a midair keyboard with your index fingers. However, midair keyboards deprive users of the tactile feedback of physical devices. We investigated providing tactile feedback by positioning a virtual keyboard on a table or wall. The keyboard was deterministic (without auto-correct), supported mixed-case typing with symbols, and relied only on the hand-tracking provided by a commodity headset's egocentric cameras. Users typed fastest with the midair keyboard, achieving a mean entry rate of 12 words per minute, and preferred it overall. Mean character error rates were below 1% in all conditions.

CCS Concepts

• **Human-centered computing** → **Text input**; **Mixed / augmented reality**.

Keywords

mixed reality (MR), augmented reality (AR), text entry, midair virtual keyboard

ACM Reference Format:
Joshua Reynolds, Scott A. Kuhl, and Keith Vertanen. 2026. Exploring Virtual Keyboard Position in Mixed Reality. In *Companion Proceedings of the Conference on Interactive Surfaces and Spaces (ISS Companion '26), November 23–26, 2026, Turin, Italy*. ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3845796.3859297

1 Introduction and background

Mixed reality (MR) allows interaction with virtual objects projected onto the real world. As MR technology develops, people might wish to use MR to perform everyday tasks. Typing is critical to many common computing tasks. Unlike a traditional keyboard where you can feel the locations of the keys and when they are actuated, MR systems often employ midair keyboards which lack tactile feedback. This can impair typing accuracy [6, 22]. We investigate whether locating a virtual keyboard over a physical horizontal or vertical surface improves typing compared to a midair keyboard.

Midair keyboards are a common MR text entry method. Dudley et al. [8] did one of the first investigations using only a headset's built-in sensors. Despite the HoloLens 1 only tracking wrist position, users typed at 18 WPM using auto-correction and word predictions. Subsequent auto-correcting keyboard studies have reported speeds of around 26 WPM [9, 30]. Richardson et al. [24] investigated surface typing using external cameras, a neural hand motion model, and a language model. Users typed at 73 WPM at a 2% error rate. In follow-up work, Richardson et al. [23] used only a VR headset's sensors and demonstrated typing at 44 WPM with a 7% error rate. While the system had no explicit language model, the motion model may have learned one; non-language text had an error rate of 16% compared to 5% on English.

Besides a virtual keyboard, there are many other ways to enter text in mixed reality. Speech input is one option, but may not always be socially acceptable [4] and can struggle with difficult words [1]. Auxiliary devices could be used such as physical keyboards [12, 16, 21, 27], controllers [25, 29], gloves [13, 19, 20], or watches [3]. Other solutions include word-gesture keyboards [3, 9], dwell-free gaze typing [14], and finger gestures [10, 13, 20].

Compared with prior work, we focus on mixed reality typing with the following characteristics:

(1) Builds on users' familiarity with tapping on a virtual keyboard.
(2) Uses only sensors built into the headset.
(3) Supports arbitrary character sequences without relying on a language model to compensate for noisy input.
(4) Supports mixed-case text, symbols, and numbers.
(5) Supports typing on horizontal and vertical surfaces.
(6) Accommodates seated use with optional arm support from a table.

We focus on typing with just the index fingers as this approach is common in past studies [1, 8, 17] and is a typical default on commercial devices. It also avoids problems with unintentional coactivations during ten-finger midair typing [11].

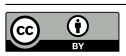
Our contributions are as follows:

(1) We show rich text can be typed accurately at 12 words per minute on a deterministic midair keyboard.
(2) While users liked the tactile feedback of a surface, midair typing was faster using a commodity headset.
(3) We release detailed study logs, study results, questionnaires, and the source code of our HoloLens application.[1]

2 Study and interface design

Our primary goal was to assess the impact of different keyboard positions, including on a horizontal and vertical surface. Since midair typing is currently a common choice for MR typing applications, we used a midair keyboard as a baseline. The study was approved by our Institutional Review Board (IRB). The study had three conditions (Figure 1):

[1] https://doi.org/10.5281/zenodo.23404905



This work is licensed under a Creative Commons Attribution 4.0 International License.
ISS Companion '26, Turin, Italy
© 2026 Copyright held by the owner/author(s).
ACM ISBN 979-8-4007-3011-5/2026/11
https://doi.org/10.1145/3845796.3859297

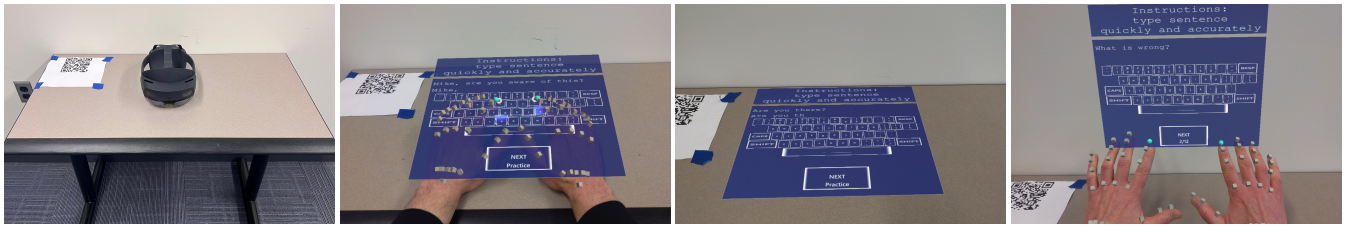


Figure 1: From left to right: the table and HoloLens headset, the Midair condition, the Table condition, and the Wall condition.

- **Midair** — The keyboard appeared in midair in front of the participant. The keyboard was horizontally centered above the table. The bottom of the spacebar was 19.0 cm from the front of the table and 4.5 cm above the table. The keyboard was angled 15 degrees above horizontal. In pilot testing, we found this angle was comfortable while typing seated. A similar angle was used in a study where users typed on or above a surface while seated (see Figure 5 in [6]).
- **Table** — The keyboard was placed just above a table. The keyboard was horizontally centered on the table. The bottom of the spacebar was 28.5 cm from the front of the table.
- **Wall** — The keyboard was placed slightly in front of a wall. The keyboard was horizontally centered on the table with the bottom of the spacebar being 16.0 cm above the table.

In all conditions, the keyboard position and small table allowed users to rest their arms on the table while typing if they wished. Participants typed with just their index fingers. Our keyboard was deterministic and did not perform auto-correction or predict words. A key was triggered when either index finger entered the key's bounding area, pushed the key's face a certain depth, and exited the same key's bounding area. On a key press, we played a sound and displayed a white border around the key. We displayed participants' hands using the Unity MR toolkit's default hand skin, an overlay of white and grey triangles. We displayed blue spheres on index fingertips and grey cubes at joints.

The keyboard size (four character rows plus spacebar) was 33.0 × 11.0 cm with 2.2 cm letter keys. The keyboard size was similar to a physical desktop keyboard. The key size was similar to past work, e.g. 2.2 cm [8], 2.5 cm [6], and 1.9 cm [23]. The keyboard was shown in blue with white key labels. It was a full QWERTY layout including numbers, symbols, shift keys, caps lock, and backspace. Users could see their current text above the keyboard and could correct errors using backspace. Participants used a HoloLens 2 headset while seated at a small 91 × 51 cm table (Figure 1 left). Before each condition, participants looked at a QR code on the table to provide for consistent keyboard placement.

The study lasted about one hour. Participants first completed a questionnaire covering demographics, English ability, and prior VR/AR use. Condition order was fully counterbalanced. Before each condition, participants typed "calibrate". We used the average key press depth to set the keyboard height above the surface in the Wall and Table conditions. We instructed participants to push a key until they felt the surface. Participants also typed "calibrate" in Midair for consistency.

In each condition, participants typed two practice sentences and twelve evaluation sentences. We analyzed only evaluation sentences. Sentences were pulled randomly without replacement from `mem1-5` in the mobile Enron dataset [26]. These sentences were in mixed case and included punctuation and sometimes numbers. During the practice and evaluation portions, we reminded participants they could type with both hands. Between conditions, participants took a two-minute break in which they lifted the HoloLens visor to reduce eyestrain. Participants then completed a questionnaire about the previous condition. After all conditions, participants completed a final questionnaire and received a $15 USD gift card.

We tested for statistical differences between conditions using a one-way repeated-measures ANOVA. In cases where Mauchly's test indicated a violation of sphericity, we report Greenhouse-Geisser corrected tests. For significant omnibus tests, we used Bonferroni-corrected post-hoc tests. For Likert ratings, we used a non-parametric Friedman's ANOVA test. For significant omnibus tests, we used Bonferroni-corrected non-parametric Wilcoxon signed-rank post-hoc tests.

3 Results

Participants. We recruited 18 participants aged 18–26. 15 participants identified as male, 2 as female, and 1 as non-binary. 16 participants strongly agreed with the statement "I consider myself a fluent speaker of English," one participant agreed, and one participant strongly disagreed. We suspect the participant who strongly disagreed made an error when marking the scale. 16 of the 18 participants reported prior experience with virtual reality (VR) — primarily with gaming headsets such as the Oculus Quest, Oculus Rift, and HTC Vive. Eight of the 18 participants reported experience with augmented reality (AR), primarily through mobile phone applications such as Pokémon Go or Minecraft Earth.

Entry rate. We measured entry rate in words per minute (WPM). We considered a word to be five characters (including space) and subtracted one from the number of characters to compensate for the unmeasured time of typing the first key [28]. We timed from the first key press until the participant pressed the Next button. Timing through the Next-button press allowed us to include the perceptual, cognitive, and motor overheads associated with confirming the last character. Entry rates were 12.2, 9.1, and 7.8 WPM in the Midair, Table, and Wall conditions respectively (Figure 2 left). This difference was significant (Table 1 left). Post-hoc tests found Midair was significantly faster than both Table and Wall.

Error rate. We measured typing errors using character error rate (CER). CER is the number of character insertions, substitutions, and

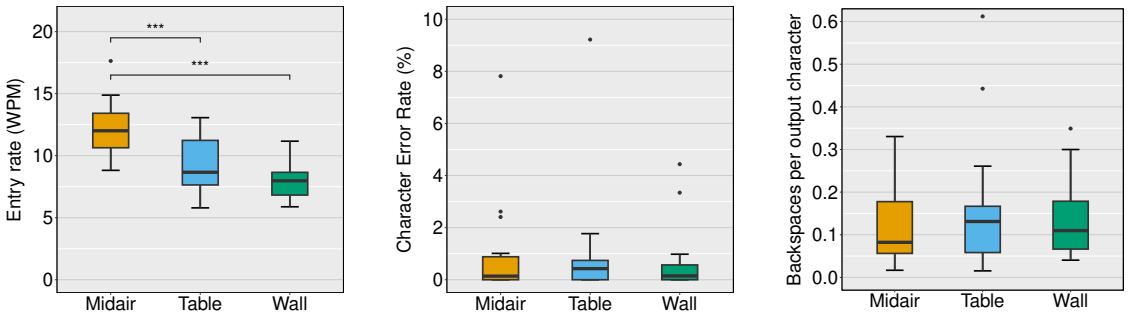


Figure 2: Entry rate (left), error rate (center), and backspaces per final output character (right). * is significant at $p < 0.001$.**

Table 1: Study results (top) and statistical test details (bottom). Results are formatted as: mean ± sd [min, max].

	Entry rate (WPM)	Error rate (CER %)	Backspaces per final character
Midair	12.2 ± 2.1 [8.8, 17.6]	0.95 ± 1.9 [0.0, 7.8]	0.119 ± 0.092 [0.017, 0.330]
Table	9.1 ± 2.2 [5.8, 13.1]	0.98 ± 2.1 [0.0, 9.2]	0.160 ± 0.151 [0.015, 0.612]
Wall	7.8 ± 1.3 [5.9, 11.2]	0.65 ± 1.2 [0.0, 4.4]	0.132 ± 0.091 [0.040, 0.349]
Omnibus test	$F_{2,34} = 31.3$, $\eta^2_G = .48$, $p < .001$	$F_{2,34} = .89$, $\eta^2_G = .007$, $p = .42$	$F_{1.4,24.2} = 1.73$, $\eta^2_G = .02$, $p = .20$
Pairwise post-hoc tests	Midair > Table, $p < .001$ Midair > Wall, $p < .001$ Table ≈ Wall, $p = .12$	n/a	n/a

deletions required to change the final entered text to the reference text, divided by the characters in the reference and multiplied by 100. Error rates were low in all conditions with a CER of 0.95%, 0.98%, and 0.65% in Midair, Table, and Wall respectively (Figure 2 center). This difference was not significant (Table 1 center).

Per-user results. Figure 3 shows each participant's performance in each condition. In Midair, all but two participants wrote at 10 WPM or faster with a CER of less than 3%. All but two participants had a final character error rate below 5% in every condition. In all conditions, many participants corrected all errors to achieve exactly the requested text (including capitalization and punctuation). This demonstrates typing on a virtual keyboard is a viable, albeit somewhat slow, mixed reality text entry method for text that cannot be auto-corrected (e.g. passwords, account numbers, and URLs).

Correction rate. As a measure of how much effort participants were expending correcting errors, we calculated the number of backspaces per final output character for each phrase. While the final character error rates in the conditions were relatively low, we observed frequent use of backspace. The number of backspaces pressed per output character was 0.12 for Midair, 0.16 for Table, and 0.13 for Wall. This difference was not significant (Table 1 right).

Hand-tracking success. We recorded participants' left and right index finger positions 30 times per second, including noting whether tracking was lost for either finger. We computed the percentage of samples where at least one finger was tracked. Participants' tracking success percentages were 99.9%, 99.1%, and 98.6% in Midair, Table, and Wall respectively. While this difference

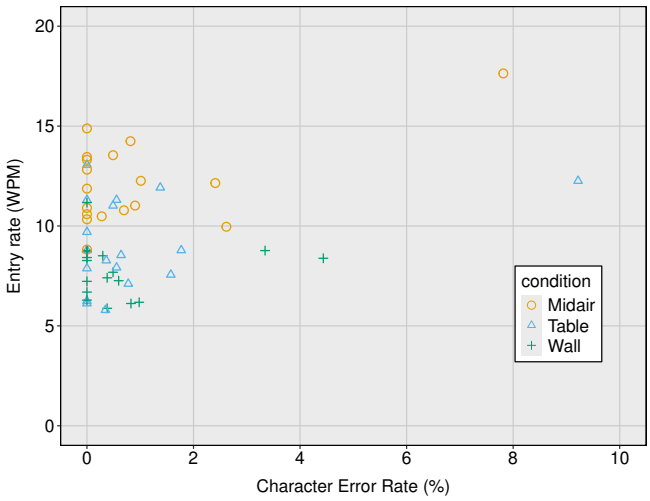
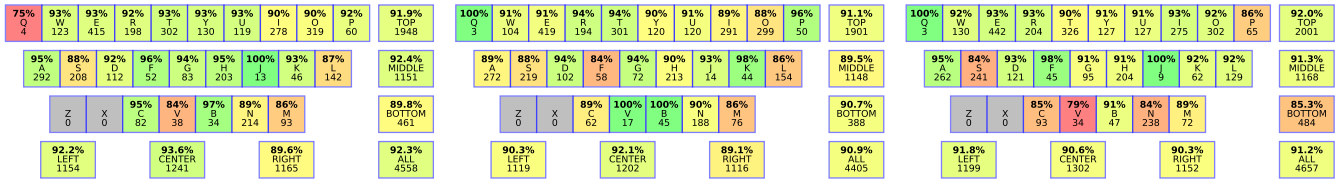


Figure 3: Entry and error rate of each participant in each condition.

was significant ($F_{2,34} = 4.23$, $\eta^2_G = 0.10$, $p < 0.05$), post-hoc pairwise comparisons were not significant: Midair ≈ Table ($p = 0.26$), Midair ≈ Wall ($p = 0.07$), and Table ≈ Wall ($p = 0.69$). We note that just because we tracked at least one finger, this does not mean the returned location was necessarily accurate.

Accuracy over keyboard. To investigate if accuracy was impacted by spatial location, we calculated the percentage of evaluated key presses that successfully entered the next character in the target



(a) Midair (b) Table (c) Wall

Figure 4: Accuracy of key presses in each condition. The integer gives the number of events the percentage is calculated from. We also grouped attempts by keyboard row and by horizontal area. For the top and middle rows, the three leftmost and rightmost keys were the left and right areas respectively. For the bottom row, the two leftmost and rightmost keys were the left and right areas respectively. The ALL box includes characters not depicted such as punctuation and numbers.

phrase. We calculated this only on key presses in which, at the time of the key press, a participant's current typing result was a strict prefix of the target. This filtering allowed reasonable confidence about a participant's next intended key. As shown in Figure 4, there did not seem to be a strong difference in accuracy based on spatial location in Midair or Table. However, in the Wall condition, the bottom keyboard row was noticeably less accurate at 85% versus 91% for the middle row and 92% for the top row.

Likert statements. After each condition, participants rated three statements on a 7-point Likert scale. Participants' average ratings for "I entered text quickly" were: Table 4.0, Wall 2.9, and Midair 5.1. The difference was significant ($\chi^2(2) = 25.9, p < 0.001$). The only significant post-hoc test was that Midair was rated as quicker than Wall ($p < 0.001$). Participants' average ratings for "I entered text accurately" were: Table 4.5, Wall 3.8, and Midair 5.4. The difference between ratings was significant ($\chi^2(2) = 9.2, p < 0.01$). The only significant post-hoc test was that Midair was rated as more accurate than Wall ($p < 0.05$). Participants' average ratings for "Entering text was physically easy and not tiring" were: Table 4.3, Wall 2.9, and Midair 4.4. The difference between ratings was significant ($\chi^2(2) = 10.9, p < 0.01$). The only significant post-hoc test was that Midair was rated as physically easier than Wall ($p < 0.05$).

Condition ranking. We asked participants to rank the conditions and to explain their reasoning. Of the 18 participants, 13 preferred Midair, 5 preferred Table, and none preferred Wall. Of those who ranked Midair the best, some representative comments were: "midair was the fastest and tracked most accurately", and "hovering was most comfortable and easy to use". Of those ranking Table as the best, participants commented: "horizontal was natural feeling and responsive", and "horizontal provided the most comfort and accuracy for me". Most participants ranked Wall as the worst and participants often mentioned physical strain: "vertical was the slowest and most physically taxing", and "wall was neither comfortable nor accurate".

Likes and dislikes. After each condition, we asked participants what they liked and disliked. One author qualitatively coded responses and another reviewed the codings and made improvements. Fatigue was mentioned by 8, 6, and 2 participants in Wall, Midair, and Table respectively. There was mixed feedback about the tactile feedback. 8 participants said they liked the tactile feedback in Wall and 4 liked it in Table. For example, one participant liked that they could "touch the wall instead of nothing" and another liked the "physical sensation of touching the table." None complained about haptic feedback in Wall or Table. However, in Midair, three people reported liking no tactile feedback and one disliked not having tactile feedback. We counted mentions of poor tracking (e.g. unexpected presses, undetected presses, or poor tracking in general). 9, 5, and 13 participants reported poor tracking in Wall, Midair, and Table respectively.

AR improvements. Finally, we asked participants "what needs to be improved or changed about the AR headset's hardware or software before you would be willing to use it in place of your mobile phone?" Suggested changes and the number of participants requesting them were:

- Improved hand-tracking accuracy and responsiveness (N=10).
- Interaction with multiple fingers (N=10).
- Improvements to the visual capabilities of the headset (N=6).
- Auto-correct or word predictions (N=3).
- Ability to locate the keyboard wherever you wanted it (N=1).
- Swipe (word-gesture keyboard) typing (N=1).
- Smaller form factor headset (N=1).

4 Discussion and limitations

Our hypothesis was a keyboard above a surface would outperform one in midair. However, we found Midair had a significantly higher entry rate than Table and Wall. Further, 13 of 18 participants preferred Midair, while the remaining 5 preferred Table. Although Wall was ranked last, it was also the condition with the most people mentioning how they liked the tactile feedback. We observed that Table and Wall reduced the reliability of key actuation and this was corroborated by participant feedback. This likely explains the decreased performance and preference in these conditions. On the plus side, all conditions had low final error rates, though we observed moderate use of backspace.

In our pilot testing, our calibration process did a good job aligning the keyboard slightly above the surface. However, in the study, we observed it worked less well for some participants. In particular, if a participant made quick hand movements, when the hand abruptly stopped, latency in the tracking system could result in overestimated press depth. Kim et al. [15] report a latency of 90 ms and tracking jitter of 1 mm using a HoloLens 2. It might be possible to improve the keyboard's placement above the surface with a modified calibration procedure, or by improved hand tracking.

It also may be advisable to allow users to interactively adjust the keyboard height during typing.

We explicitly chose not to employ auto-correct in our study. We argue any text entry interface intended for general use must support deterministic input. This can be necessary for certain types of content, or to avoid an auto-correct trap in which a user's desired and correct text is repeatedly auto "corrected" into incorrect text. Our work can help guide how an auto-correcting MR keyboard can best support fallback to deterministic input. While our midair entry rate of 12 WPM is modest, users almost always obtained their target text including case and symbols. To our knowledge, this is the first study to test midair keyboard entry on this style of English text. Past work with deterministic midair keyboards on English phrases without mixed case or symbols found entry rates of 11 WPM [5] and 10 WPM [25].

The sometimes unreliable key triggering may be related to limitations of the HoloLens' egocentric cameras or its hand-tracking models. During the study, we saw participants try to compensate for hand-tracking issues in a number of ways, such as moving closer to the keyboard or adjusting the viewing angle between the headset and the keyboard. However, in some cases, such adjustments made tracking less reliable. Ideally, the HoloLens interface would provide some sort of feedback that helps users adjust their position to improve tracking.

Past work on midair keyboards has commonly oriented keyboards either completely vertically [2, 18] or tilted slightly away from vertical [1, 8]. However, in most past studies, participants were standing and not seated as in our study. We used a 15-degree tilt from horizontal. This angle felt comfortable in pilot testing and more closely matches users' real-world typing experience on desktop keyboards which often have an upward tilt. A similar 20-degree tilt was used in a study of seated typing on or near a surface [6, 7]. While this tilt appeared to work well for our participants, further exploration of user performance and preference with regard to keyboard tilt may be useful.

Our study participants sat at a small table in all conditions, including the Midair condition. We chose a seated posture because it is common for everyday text input and allowed participants to support their arms on the table in all conditions. However, this posture may have favored the Table condition relative to the Midair and Wall conditions. Future work could compare different keyboard locations both while seated and while standing.

Our study consisted of a single one-hour session. The majority of our participants had no prior mixed reality experience. For index-finger typing on a midair keyboard, it was reassuring to see that novices could achieve a functional level of text entry performance with little training. Furthermore, they did this on text requiring use of mixed case, punctuation, and numbers. However, it would be interesting to study virtual keyboard performance over a longer period of time to better understand whether better performance is attainable with practice.

An interesting avenue for future research would be to use auxiliary sensors (e.g. the AR headset's microphone or a smartwatch) to detect taps on a physical surface instead of, or in addition to, finger collision with the keys. This could improve tap detection accuracy of virtual targets positioned on physical surfaces. In particular, the tactile feedback of actual contact with a surface could mitigate the problem of unintentional key presses in ten-finger typing.

5 Conclusion

We showed that a midair keyboard had significantly higher entry rates and was preferred over keyboards positioned on a surface. Entry rates were 12.2, 9.1, and 7.8 WPM in the Midair, Table, and Wall conditions respectively. Participants did this on real-world text involving mixed case, punctuation, and numbers. Furthermore, they did this on a deterministic keyboard without auto-correct. Questionnaire results also showed that our midair keyboard, which was arranged such that participants could rest their arms on a table, was preferred and not particularly tiring compared to the keyboards positioned on a wall or table. Participant feedback was generally positive about the tactile feedback and ergonomics of typing on a virtual keyboard located on a surface. However, at present, the hand-tracking of a current commodity headset (HoloLens 2) needs improvement to better support accurate deterministic interactions near surfaces.

Acknowledgments

This material is based upon work supported by the NSF under Grant No. IIS-1909089.

References

[1] Jiban Adhikary and Keith Vertanen. 2021. Text Entry in Virtual Environments using Speech and a Midair Keyboard. *IEEE Transactions on Visualization and Computer Graphics* 27, 5 (2021), 2648–2658. doi:10.1109/TVCG.2021.3067776

[2] Jiban Adhikary and Keith Vertanen. 2021. Typing on Midair Virtual Keyboards: Exploring Visual Designs and Interaction Styles. In *Human-Computer Interaction – INTERACT 2021: 18th IFIP TC 13 International Conference, Bari, Italy, August 30 – September 3, 2021, Proceedings, Part IV* (Bari, Italy). Springer-Verlag, Berlin, Heidelberg, 132–151. doi:10.1007/978-3-030-85610-6_9

[3] Sunggeun Ahn, Seongkook Heo, and Geehyuk Lee. 2017. Typing on a Smartwatch for Smart Glasses. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces* (Brighton, United Kingdom) *(ISS '17)*. ACM, New York, NY, USA, 201–209. doi:10.1145/3132272.3134136

[4] Monique Faye Baier and Michael Burmester. 2019. Not Just About the User: Acceptance of Speech Interaction in Public Spaces. In *Proceedings of Mensch Und Computer 2019* (Hamburg, Germany) *(MuC '19)*. Association for Computing Machinery, New York, NY, USA, 349–359. doi:10.1145/3340764.3340801

[5] Tafadzwa Joseph Dube and Ahmed Sabbir Arif. 2023. Ultrasonic Keyboard: A Mid-Air Virtual Qwerty with Ultrasonic Feedback for Virtual Reality. In *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '23)*. Association for Computing Machinery, New York, NY, USA, Article 47, 8 pages. doi:10.1145/3569009.3573117

[6] John Dudley, Hrvoje Benko, Daniel Wigdor, and Per Ola Kristensson. 2019. Performance Envelopes of Virtual Keyboard Text Input Strategies in Virtual Reality. In *2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, Piscataway, NJ, USA, 289–300. doi:10.1109/ISMAR.2019.00027

[7] John J. Dudley. 2025. Personal communication. Email correspondence.

[8] John J. Dudley, Keith Vertanen, and Per Ola Kristensson. 2018. Fast and Precise Touch-Based Text Entry for Head-Mounted Augmented Reality with Variable Occlusion. *ACM Transactions on Computer-Human Interaction (TOCHI)* 25, 6, Article 30 (Dec. 2018), 40 pages. doi:10.1145/3232163

[9] John J. Dudley, Jingyao Zheng, Aakar Gupta, Hrvoje Benko, Matt Longest, Robert Wang, and Per Ola Kristensson. 2023. Evaluating the Performance of Hand-Based Probabilistic Text Input Methods on a Mid-Air Virtual Qwerty Keyboard. *IEEE Transactions on Visualization and Computer Graphics* 29, 11 (Nov. 2023), 4567–4577. doi:10.1109/TVCG.2023.3320238

[10] Anna Maria Feit, Srinath Sridhar, Christian Theobalt, and Antti Oulasvirta. 2015. Text is in the Air... Investigating Multi-Finger Gestures for Mid-Air Text Entry. Paper presented at ACM womENcourage Celebration of Women in Computing, Uppsala, Sweden, 4 pages. https://womencourage.acm.org/archive/2015/pdf/papers/paper_2b.pdf

[11] Conor R. Foy, John J. Dudley, Aakar Gupta, Hrvoje Benko, and Per Ola Kristensson. 2021. Understanding, Detecting and Mitigating the Effects of Coactivations in Ten-Finger Mid-Air Typing in Virtual Reality. In *Proceedings of the 2021 CHI*

Conference on Human Factors in Computing Systems (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 287, 11 pages. doi:10.1145/3411764.3445671

[12] Jens Grubert, Lukas Witzani, Eyal Ofek, Michel Pahud, Matthias Kranz, and Per Ola Kristensson. 2018. Text Entry in Immersive Head-Mounted Display-Based Virtual Reality Using Standard Keyboards. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Piscataway, NJ, USA, 159–166. doi:10.1109/VR.2018.8446059

[13] Zhenyi He, Christof Lutteroth, and Ken Perlin. 2022. TapGazer: Text Entry with Finger Tapping and Gaze-directed Word Selection. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 337, 16 pages. doi:10.1145/3491102.3501838

[14] Jinghui Hu, John J. Dudley, and Per Ola Kristensson. 2024. SkiMR: Dwell-free Eye Typing in Mixed Reality. In *2024 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*. IEEE, Piscataway, NJ, USA, 439–449. doi:10.1109/VR58804.2024.00065

[15] Taejun Kim, Amy Karlson, Aakar Gupta, Tovi Grossman, Jason Wu, Parastoo Abtahi, Christopher Collins, Michael Glueck, and Hemant Bhaskar Surale. 2023. STAR: Smartphone-analogous Typing in Augmented Reality. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 116, 13 pages. doi:10.1145/3586183.3606803

[16] Pascal Knierim, Valentin Schwind, Anna Maria Feit, Florian Nieuwenhuizen, and Niels Henze. 2018. Physical Keyboards in Virtual Reality: Analysis of Typing Performance and Effects of Avatar Hands. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal, QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, Article 345, 9 pages. doi:10.1145/3173574.3173919

[17] Mathias N. Lystbæk, Ken Pfeuffer, Jens Emil Sloth Grønbæk, and Hans Gellersen. 2022. Exploring Gaze for Assisting Freehand Selection-based Text Entry in AR. *Proceedings of the ACM on Human-Computer Interaction* 6, ETRA, Article 141 (May 2022), 16 pages. doi:10.1145/3530882

[18] Anders Markussen, Mikkel R Jakobsen, and Kasper Hornbæk. 2013. Selection-based Mid-air Text Entry on Large Displays. In *IFIP Conference on Human-Computer Interaction – INTERACT 2013*. Springer, Berlin, Heidelberg, 401–418. doi:10.1007/978-3-642-40483-2_28

[19] Anders Markussen, Mikkel Rønne Jakobsen, and Kasper Hornbæk. 2014. Vulture: A Mid-Air Word-Gesture Keyboard. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI '14)*. ACM, New York, NY, USA, 1073–1082. doi:10.1145/2556288.2556964

[20] Barry McCaul and Alistair Sutherland. 2004. Predictive Text Entry in Immersive Environments. In *IEEE Virtual Reality 2004*. IEEE, Piscataway, NJ, USA, 241–242. doi:10.1109/VR.2004.60

[21] Mark McGill, Daniel Boland, Roderick Murray-Smith, and Stephen Brewster. 2015. A Dose of Reality: Overcoming Usability Challenges in VR Head-Mounted Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. ACM, New York, NY, USA, 2143–2152. doi:10.1145/2702123.2702382

[22] Ely Rabin and Andrew Gordon. 2004. Tactile feedback contributes to consistency of finger movements during typing. *Experimental Brain Research* 155 (2004), 362–369. doi:10.1007/s00221-003-1736-6

[23] Mark Richardson, Fadi Botros, Yangyang Shi, Pinhao Guo, Bradford J. Snow, Linguang Zhang, Jingming Dong, Keith Vertanen, Shugao Ma, and Robert Wang. 2024. StegoType: Surface Typing from Egocentric Cameras. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology (UIST '24)*. Association for Computing Machinery, New York, NY, USA, Article 83, 14 pages. doi:10.1145/3654777.3676343

[24] Mark Richardson, Matt Durasoff, and Robert Wang. 2020. Decoding Surface Touch Typing from Hand-Tracking. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology (UIST '20)*. Association for Computing Machinery, New York, NY, USA, 686–696. doi:10.1145/3379337.3415816

[25] Marco Speicher, Anna Maria Feit, Pascal Ziegler, and Antonio Krüger. 2018. Selection-based Text Entry in Virtual Reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal, QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, Article 647, 13 pages. doi:10.1145/3173574.3174221

[26] Keith Vertanen and Per Ola Kristensson. 2011. A versatile dataset for text entry evaluations based on genuine mobile emails. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services* (Stockholm, Sweden) *(MobileHCI '11)*. Association for Computing Machinery, New York, NY, USA, 295–298. doi:10.1145/2037373.2037418

[27] James Walker, Bochao Li, Keith Vertanen, and Scott Kuhl. 2017. Efficient Typing on a Visually Occluded Physical Keyboard. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 5457–5461. doi:10.1145/3025453.3025783

[28] Jacob O. Wobbrock. 2007. Measures of Text Entry Performance. In *Text Entry Systems: Mobility, Accessibility, Universality*, I. Scott MacKenzie and Kumiko Tanaka-Ishii (Eds.). Morgan Kaufmann, San Francisco, CA, USA, Chapter 3, 47–74. doi:10.1016/B978-012373591-1/50003-6

[29] Wenge Xu, Hai-Ning Liang, Anqi He, and Zifan Wang. 2019. Pointing and Selection Methods for Text Entry in Augmented Reality Head Mounted Displays. In *2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, Piscataway, NJ, USA, 279–288. doi:10.1109/ISMAR.2019.00026

[30] Xin Yi, Chen Liang, Haozhan Chen, Jiuxu Song, Chun Yu, Hewu Li, and Yuanchun Shi. 2023. From 2D to 3D: Facilitating Single-Finger Mid-Air Typing on QWERTY Keyboards with Probabilistic Touch Modeling. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 7, 1, Article 38 (March 2023), 25 pages. doi:10.1145/3580829