Improving the accessibility of virtual reality for people with motor and visual impairments

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Abstract

Virtual reality (VR), and especially the Metaverse, offers a new set of experiences for users who can operate in immersive 3-D environments, but such environments must be made accessible for movement and observation. To this end, we are pursuing a research program to understand and improve the accessibility of VR for two user groups: (1) people with motor impairments, who might face difficulty moving through virtual environments, and (2) people who are blind or have low vision (BLV), and thus cannot see virtual environments. To date, we have conducted studies on locomotion techniques in VR, gathering data to build predictive models capable of matching users' abilities to their most suitable techniques. We are also developing a smartphone-based VR controller, supporting touch-based "scene reading" as an analog to "screen reading" to enable BLV users to understand and move through virtual environments. This workshop paper reviews our efforts and posits avenues for future research.

Keywords

virtual reality, virtual environments, motor impairments, blindness, low vision, scene reading

1. Introduction

Virtual reality (VR), and especially the Metaverse, hold great promise for making possible new experiences previously unimagined. People can meet in virtual environments to learn [29], play [30], work [7], travel [27], and socialize [34]. VR has also been used for both mental [6,28] and physical [18,33] therapeutic purposes. VR has been around for decades [26], and very early its promise to provide benefits to people with disabilities was observed [25]. But realizing those benefits requires VR, and large-scale environments like the Metaverse, to be made accessible for *movement* and *observation*. Unfortunately, as is often the case with new media, virtual environments like the Metaverse are largely inaccessible to people with motor and visual impairments. If these environments are to deliver their full potential, they must become accessible to *all* users [23].

ACM CHI 2024 Workshop on Building a Metaverse for All, May 11, 2024, Honolulu, HI

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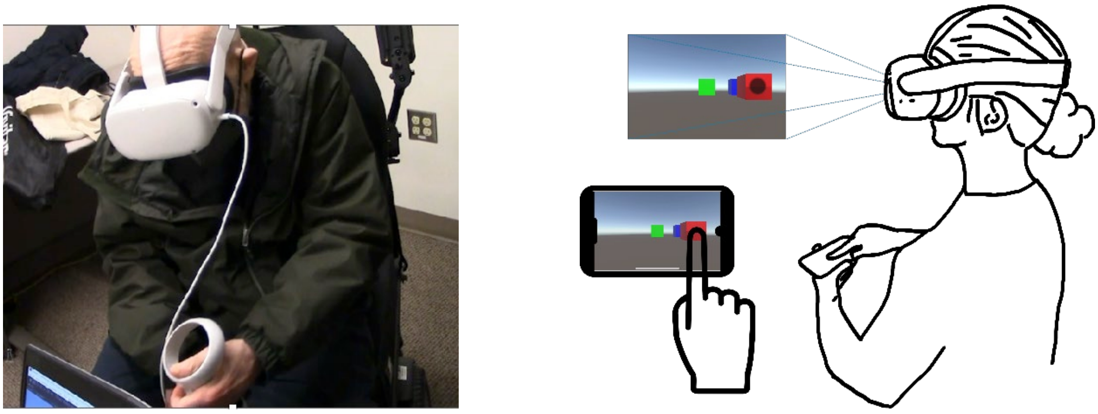

Figure 1: (*left*) A study participant using *Grab and Pull* reaches forward and pulls the ground towards himself to move. (*right*) Sketch of our prototype system using a smartphone as a touch-based controller for "scene reading," object selection, and navigation. (The headset view is displayed on the smartphone to enable sighted observation.)

To this end, we are pursuing a research program to understand and improve the accessibility of VR for people with motor impairments and for people who are blind or have low vision (BLV). Specifically, we have experimentally studied the use of locomotion techniques by people with limited upper-body motor function [11], developing predictive models that can recommend a locomotion technique for a user given that user's answers on a questionnaire [12] or actions with VR hardware (Fig. 1, *left*).

In other work, we are developing a novel touch-based controller for BLV users that enables a user's smartphone to replace conventional button-based controllers (Fig. 1, *right*). By using a smartphone in landscape orientation, BLV users can explore virtual environments using touch and gesture, receiving auditory and vibrotactile feedback. Specifically, we are creating a method of "scene reading" (as an analog to "screen reading"), whereby BLV users can explore virtual scenes with their fingers, much like our *Slide Rule* prototype [21] enabled finger-driven screen reading on smartphones.

2. Related work

We review related work focused on accessible locomotion techniques and the accessibility of VR for BLV users. Due to limitations of space, a full review is prohibited; readers are directed to thorough treatments elsewhere [5,10,11].

There are over one hundred locomotion techniques for VR [5], although relatively few research efforts have attempted to understand their accessibility to people with motor impairments. Di Luca et al. [5] examined the amount of motion required for numerous locomotion techniques to assess their accessibility. Franz et al. [10] created a taxonomy of scene viewing techniques and applied it to the accessibility of head movements in VR, evaluating techniques with 16 participants to identify accessibility tradeoffs. Mott et al. [24] conducted semi-structured interviews to uncover physical accessibility barriers with VR devices like headsets and controllers. They drew upon our ability-based design perspective [37,38] to uncover "ability assumptions" in the design of VR devices. Franz et al. [9] devised

Nearmi, a framework for creating accessible point-of-interest viewing techniques. By contrast, our work [11] empirically evaluates locomotion techniques for their accessibility, and creates predictive models to aid in the selection of such techniques for specific users.

Some researchers have undertaken the challenge of making VR accessible to BLV users. *SeeingVR* [42] offered 14 tools for low-vision users to modify virtual environments with video and audio enhancements. *HOMERE* [22] combined force, thermal, and auditory feedback to simulate sensations through a cane. *Canetroller* [41] was also a physical cane for use in VR, providing haptic feedback in response to virtual objects and surfaces. Early examples of haptic feedback for BLV VR users were from Colwell et al. [4] and Jansson et al. [19], where virtual textures and objects were simulated with the Impulse Engine 3000 and PHANToM 1.5, respectively. Haptics were also explored by Tzovaras et al. [36] using a CyberGrasp device. More recently, Collins et al. [3] explored how sighted guides in VR can enhance social interactions for BLV users. And Herskovitz et al. [17] studied how blind users can use augmented reality with guided prompting. By contrast, our ongoing work explores the use of a smartphone's touch screen to act as both an input and output device, enabling finger-driven "scene reading," object selection, and navigation.

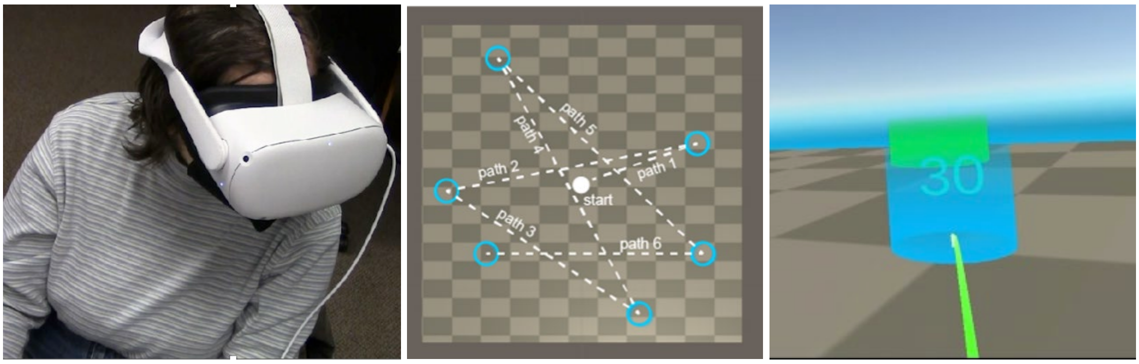

Figure 2: (*left*) A study participant leans forward to move in her gaze direction with *Chicken Acceleration*. (*middle*) Target order and positions in one of our studies. (*right*) A user aims their controller where they want to go and presses a trigger to jump to that position with *Teleport*.

3. Understanding locomotion techniques for users with motor impairments in virtual reality

To better understand the accessibility of locomotion techniques for users with motor impairments, we conducted a formal experiment of six seated locomotion techniques with 20 participants [11] (Fig. 2, *left*). We built a custom testbed enabling us to arrange targets and obstacles (Fig. 2, *middle*), and log movement times, paths, hits, misses, and low-level controller and headset data. Participants used a Meta Quest 2 headset connected to an Alienware m15 P79F laptop with standard controllers. The six locomotion techniques we evaluated required a range of different motor abilities:

1. *Astral Body*: Elevated third-person perspective controlled with a thumbstick.
2. *Chicken Acceleration*: Lean forward or rotate one's head to move in that direction.

3. *Grab and Pull*: Reach forward, hold the trigger, and pull the controller to oneself.
4. *Sliding Looking*: Hold a button while looking in the desired movement direction.
5. *Teleport*: Use controller to position a landing spot and press trigger to jump there.
6. *Throw Teleport*: Throw a ball with the controller and jump to where the ball lands.

In our experiment, 20 participants each completed 12 trials using each locomotion technique in a counterbalanced fashion. They then filled out a NASA-TLX workload questionnaire [15,16] and answered interview questions about their experience.

Our results show that three of our six techniques performed similarly well: *Teleport*, *Astral Body*, and *Sliding Looking*. These techniques used only one controller, required little upper-body movement, and had low perceived workload. Our post-study interviews revealed *Teleport* (Fig. 2, *right*) to be generally favored, although other factors besides accessibility mattered, such as enjoyment, exercise, and a sense of presence. Fig. 3 shows results for trial time, target hit rate, and obstacles hit.

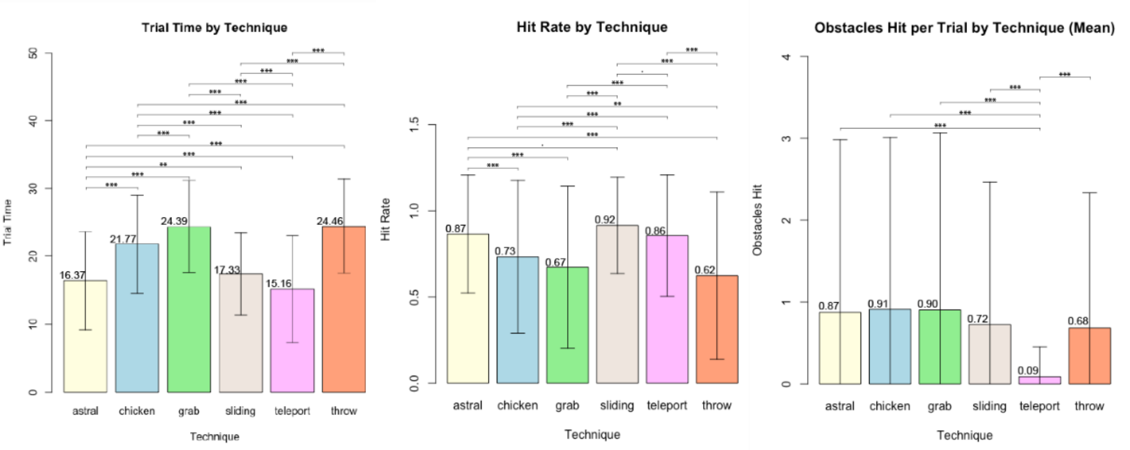

Figure 3: Compared to other techniques: (*left*) *Astral Body*, *Sliding Looking*, and *Teleport* had lower trial times. (*middle*) *Astral Body*, *Sliding Looking*, and *Teleport* had higher hit rates. (*right*) *Teleport* had the least obstacles hit.

One of the goals of our ongoing work is to see whether self-report data from a standardized questionnaire, *Quick* DASH [12], can be predictive of locomotion performance. Our preliminary results show that these 11 questions, taking only five minutes to complete, explain 30-50% of the variance in performance with our techniques. We are also examining how controller and headset movement data can improve our models, which could enable us to predict performance with only a few questions and basic movement tasks.

4. "Scene reading," object selection, and navigation for BLV users in VR

Virtual reality is an inherently visual medium, making the accessibility of virtual environments a significant challenge for BLV users. In our past work, we created *Slide Rule* [21], a finger-driven screen reader for the iPhone 1. Slide Rule allowed a "reading finger" to explore the screen while contents were announced, modified by traversal speed. A split-tap gesture, where a separate finger (or thumb) taps *anywhere* on the screen, triggers whatever target is beneath the "reading finger." In this way, users can explore the screen and trigger targets without lifting a finger.

Along similar lines, we are exploring the use of a smartphone touch screen as a controller for BLV users in VR. Touch screens have been used as input to virtual and augmented reality for some time (e.g., [2,17,35]), but have scarcely been applied to VR accessibility for BLV users. Specifically, we map the VR headset's view onto the smartphone via our custom Meta Quest 2 and Apple iOS apps (see Fig. 1, *right*). We enable gestures where one finger "reads the scene" and two fingers trigger movement.

Specifically, dragging one finger over the screen announces different objects as they are traversed using our "scene reading" technique (Fig. 4a). A split-tap provides detail on the object beneath the reading finger (Fig. 4b). Scene reading can be done on the live, dynamic scene, or on a static "snapshot" of the scene taken using a three-finger tap.

Two fingers cause movement. A two-finger tap on an object or person jumps the user to it, subsequently following it if it is in motion (Fig. 4c). If the user swipes up or down with two fingers, they move forward or backward proportionally. Similarly, pinch-to-zoom can also move the user forward or backward. A two-finger swipe left or right rotates the user discretely, or a two-finger clockwise or counterclockwise circle can rotate the user continuously and reversibly (Fig. 4d).

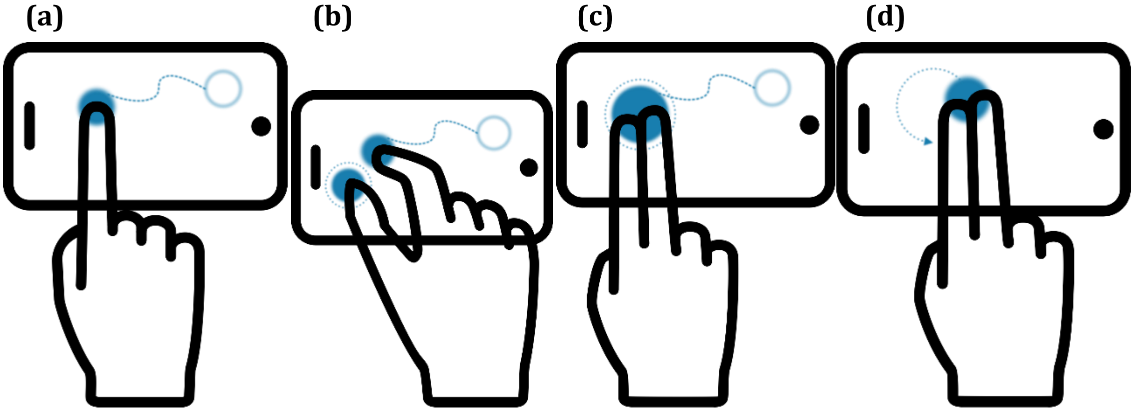

Figure 4: (*a*) One-finger "screen reading" leading to (*b*) a split-tap for further object information. (*c*) A two-finger tap jumps to that object. (*d*) A two-finger counterclockwise circle rotates the user.

Along with touch and gesture input, we employ audio output in the form of success and failure sounds, text-to-speech descriptions and instructions, and vibrotactile feedback to indicate object collisions.

Thus far, we have designed and prototyped our system, prioritizing a simple and consistent gesture vocabulary. We plan to work closely with BLV users to iteratively test and improve our prototype, as it is now capable of supporting rapid design exploration and evaluation.

5. Future work and open challenges

Our projects suggest multiple avenues for future work. For users with motor impairments, physical barriers with headsets and controllers remain problematic [24]. With the advent of lighter hardware, this issue might improve, but it is unlikely to be solved unless the accessibility of hardware is addressed as a top-level priority, perhaps through universal design, which has been used successfully before in physical product design [31,32].

Like any screen reader, our "scene reading" technique requires a labeled world. Just like how images on the Web, in mobile apps, and on social media often lack ALT text [8,40], most virtual environments, including the Metaverse, are not fully annotated, and their objects lack metadata. As with ALT text, developer compliance is unlikely to remedy the issue. A solution might be to use generative A.I. to provide object descriptions of static, "snapshotted" scenes, but the accuracy of this approach is uncertain.

Users with motor impairments and BLV users might benefit from greater use of speech recognition in VR. For the former group, locomotion might be possible through discrete speech commands, such as "take me to the birch tree," or through continuous non-speech vocalizations, such as those used in the *Vocal Joystick* [13,14,20]. For the latter group, speech recognition might enable the user to query a scene, asking, "how many people are currently around?" or "what object is directly to my right?"

Improving the accessibility of social interactions in VR is also a priority. Inaccessible locomotion techniques can make it difficult for users with motor impairments to engage with other people's avatars, and BLV users might not know who is nearby or what environmental features are being discussed. Avatar disability signifiers [39] can augment social interactions by providing awareness of a user's disability status, but do not solve the usability challenges social VR poses.

Finally, as is often the case, accessible computing research attempts to make accessible that which is inaccessible from the start, and indeed this is important [23]. But stepping back, we might ask what *experience* VR intends to provide, and then pursue good ways to provide that experience [37,38]. For example, if VR is chiefly concerned with providing a sense of *immersion*, how can we best achieve this for BLV users? By pursuing the intended experience, we can open the design space to new disability-first possibilities (e.g., [1]).

6. Conclusion

In this workshop paper, we have described our work on making VR accessible to users with motor impairments and to BLV users. We have formally studied the former group's use of six locomotion techniques, finding *Teleport*, *Astral Body*, and *Sliding Looking* to be fastest and most accurate, but that enjoyment, exercise, and a sense of presence mattered a great deal [11]. We are creating and validating predictive models that can recommend promising locomotion techniques for users based on questionnaire and other data [12]. For BLV users, we are creating a smartphone-based controller that enables touch-and-gesture "scene reading," object selection, and navigation. Multiple promising avenues exist for future work, including hardware accessibility, world labeling, speech input, social interaction, and focusing on delivering the intended experience to *all* users.

Acknowledgements

The authors thank Alexis Hiniker for discussions of future work. This work was supported in part by an Apple AI/ML Ph.D. Fellowship, a Facebook Social VR grant, and the University of Washington Center for Research and Education on Accessible Technology and Experiences (CREATE). Any opinions, findings, conclusions or recommendations expressed in this work are those of the authors and do not necessarily reflect those of any supporter.

References

1. Balasubramanian, H., Morrison, C., Grayson, M., Makhataeva, Z., Marques, R., Gable, T., Perez, D. and Cutrell, E. (2023). Enable blind users' experience in 3D virtual environments: The Scene Weaver prototype. *Extended Abstracts of the ACM Conference on Human Factors in Computing Systems (CHI EA '23)*. New York: ACM Press. Article No. 447. https://doi.org/10.1145/3544549.3583909
2. Benzina, A., Dey, A., Tönnis, M. and Klinker, G. (2012). Empirical evaluation of mapping functions for navigation in virtual reality using phones with integrated sensors. *Proceedings of the 10th Asia-Pacific Conference on Computer-Human Interaction (APCHI '12)*. New York: ACM Press, pp. 149-158. https://doi.org/10.1145/2350046.2350078
3. Collins, J., Jung, C., Jang, Y., Montour, D., Won, A.S. and Azenkot, S. (2023). "The guide has your back": Exploring how sighted guides can enhance accessibility in social virtual reality for blind and low vision people. *Proceedings of the ACM Conference on Computers and Accessibility (ASSETS '23)*. New York: ACM Press. Article No. 38. https://doi.org/10.1145/3597638.3608386
4. Colwell, C., Petrie, H., Kornbrot, D., Hardwick, A. and Furner, S. (1998). Haptic virtual reality for blind computer users. *Proceedings of the ACM Conference on Assistive Technologies (ASSETS '98)*. New York: ACM Press, pp. 92-99. https://doi.org/10.1145/274497.274515
5. Di Luca, M., Seifi, H., Egan, S. and Gonzalez-Franco, M. (2021). Locomotion Vault: the extra mile in analyzing VR locomotion techniques. *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '21)*. New York: ACM Press. Article No. 128. https://doi.org/10.1145/3411764.3445319
6. Emmelkamp, P.M.G. and Meyerbröker, K. (2021). Virtual reality therapy in mental health. *Annual Review of Clincial Psychology 17* (1), pp. 495-519. https://doi.org/10.1146/annurev-clinpsy-081219-115923
7. Fereydooni, N. and Walker, B.N. (2020). Virtual reality as a remote workspace platform: Opportunities and challenges. *Proceedings of New Future of Work*. Redmond, WA: Microsoft. https://www.microsoft.com/en-us/research/publication/virtual-reality-as-a-remote-workspace-platform-opportunities-and-challenges/
8. Fok, R., Zhong, M., Ross, A.S., Fogarty, J. and Wobbrock, J.O. (2022). A large-scale longitudinal analysis of missing label accessibility failures in Android apps. *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '22)*. New York: ACM Press. Article No. 461. https://doi.org/10.1145/3491102.3502143
9. Franz, R.L., Junuzovic, S. and Mott, M. (2021). Nearmi: A framework for designing point of interest techniques for VR users with limited mobility. *Proceedings of the ACM Conference on Computers and Accessibility (ASSETS '21)*. New York: ACM Press. Article No. 5. https://doi.org/10.1145/3441852.3471230
10. Franz, R.L., Junuzovic, S. and Mott, M. (2024). A virtual reality scene taxonomy: Identifying and designing accessible scene-viewing techniques. *ACM Transactions on Computer-Human Interaction 31* (2). Article No. 23. https://doi.org/10.1145/3635142

11. Franz, R.L., Yu, J. and Wobbrock, J.O. (2023). Comparing locomotion techniques in virtual reality for people with upper-body motor impairments. *Proceedings of the ACM Conference on Computers and Accessibility (ASSETS '23)*. New York: ACM Press. Article No. 39. https://doi.org/10.1145/3597638.3608394
12. Gummesson, C., Ward, M.M. and Atroshi, I. (2006). The shortened disabilities of the arm, shoulder and hand questionnaire (Quick DASH): validity and reliability based on responses within the full-length DASH. *BMC Musculoskeletal Disorders* 7. Article No. 44. https://doi.org/10.1186/1471-2474-7-44
13. Harada, S., Landay, J.A., Malkin, J., Li, X. and Bilmes, J.A. (2006). The Vocal Joystick: Evaluation of voice-based cursor control techniques. *Proceedings of the ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '06)*. New York: ACM Press, pp. 197-204. https://doi.org/10.1145/1168987.1169021
14. Harada, S., Wobbrock, J.O., Malkin, J., Bilmes, J.A., and Landay, J.A. (2009). Longitudinal study of people learning to use continuous voice-based cursor control. *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '09)*. New York: ACM Press, pp. 347-356. https://doi.org/10.1145/1518701.1518757
15. Hart, S.G. (2006). NASA-Task Load Index (NASA-TLX); 20 years later. *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting 50* (9), pp. 904-908. https://doi.org/10.1177/154193120605000909
16. Hart, S.G. and Staveland, L.E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In *Human Mental Workload*, P.A. Hancock and N. Meshkati (eds.). Amsterdam: North Holland Press, pp. 139-183.
17. Herskovitz, J., Wu, J., White, S., Pavel, A., Reyes, G., Guo, A. and Bigham, J.P. (2020). Making mobile augmented reality applications accessible. *Proceedings of the ACM Conference on Computers and Accessibility (ASSETS '20)*. New York: ACM Press. Article No. 3. https://doi.org/10.1145/3373625.3417006
18. Holden, M.K. (2005). Virtual environments for motor rehabilitation: review. *CyberPsychology and Behavior 8* (3), pp. 187-211. https://doi.org/10.1089/cpb.2005.8.187
19. Jansson, G., Petrie, H., Colwell, C., Kornbrot, D., Fänger, J., König, H., Billberger, K., Hardwick, A. and Furner, S. (1999). Haptic virtual environments for blind people: Exploratory experiments with two devices. *International Journal of Virtual Reality 4* (1), pp. 8-17. https://doi.org/10.20870/IJVR.1999.4.1.2663
20. Bilmes, J.A., Li, X., Malkin, J., Kilanski, K., Wright, R., Kirchhoff, K., Subramanya, A., Harada, S., Landay, J.A., Dowden, P. and Chizeck, H. (2005). The Vocal Joystick: A voice-based human-computer interface for individuals with motor impairments. *Proceedings of the Conference on Human Language Technology and Empirical Methods in Natural Language Processing (HLT/EMNLP '05)*. Stroudsburg, PA: Association for Computational Linguistics, pp. 995-1002. https://doi.org/10.3115/1220575.1220700
21. Kane, S.K., Bigham, J.P. and Wobbrock, J.O. (2008). Slide Rule: Making mobile touch screens accessible to blind people using multi-touch interaction techniques. *Proceedings of the ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '08)*. New York: ACM Press, pp. 73-80. https://doi.org/10.1145/1414471.1414487
22. Lécuyer, A., Mobuchon, P., Mégard, C., Perret, J., Andriot, C. and Colinot, J.-P. (2003). HOMERE: A multimodal system for visually impaired people to explore virtual environments. *Proceedings of IEEE Virtual Reality (VR '03)*, pp. 251-258. https://doi.org/10.1109/VR.2003.1191147
23. Mott, M., Cutrell, E., Gonzalez-Franco, M., Holz, C., Ofek, E., Stoakley, R. and Morris, M.R. (2019). Accessible by design: An opportunity for virtual reality. *Adjunct Proceedings of the IEEE*

International Symposium on Mixed and Augmented Reality (ISMAR '19). Los Alamitos, CA: IEEE Computer Society, pp. 451-454. https://doi.org/10.1109/ISMAR-Adjunct.2019.00122

24. Mott, M.E., Tang, J., Kane, S.K., Cutrell, E. and Morris, M.R. (2020). "I just went into it assuming that I wouldn't be able to have the full experience": Understanding the accessibility of virtual reality for people with limited mobility. *Proceedings of the ACM Conference on Computers and Accessibility (ASSETS '20)*. New York: ACM Press. Article No. 43. https://doi.org/10.1145/3373625.3416998
25. Nelson, J.A. (1994). The virtual community: A place for the no-longer-disabled. *Proceedings of the 2nd Annual Conference on Virtual Reality and Persons with Disabilities*. Northridge, CA: California State University Northridge, pp. 98-102.
26. Pausch, R. (1991). Virtual reality on five dollars a day. *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '91)*. New York: ACM Press, pp. 265-270. https://doi.org/10.1145/108844.108913
27. Polechoński, J. and Tomik, R. (2019). Can "tourism" in immersive virtual reality replace real travel? *Folia Turistica 52*, pp. 11-30. https://doi.org/10.5604/01.3001.0013.2639
28. Riva, G. and Serino, S. (2020). Virtual reality in the assessment, understanding and treatment of mental health disorders. *Journal of Clincial Medicine 9* (11): 3434. https://doi.org/10.3390/jcm9113434
29. Roussou, M., Oliver, M. and Slater, M. (2006). The virtual playground: An educational virtual reality environment for evaluating interactivity and conceptual learning. *Virtual Reality 10* (3-4), pp. 227-240. https://doi.org/10.1007/s10055-006-0035-5
30. Shafer, D.M., Carbonara, C.P. and Korpi, M.F. (2019). Factors affecting enjoyment of virtual reality games: A comparison involving consumer-grade virtual reality technology. *Games for Health Journal 8* (1), pp. 15-23. https://doi.org/10.1089/g4h.2017.0190
31. Stark, C. and Sarkar, S. (2018). Microsoft's new Xbox controller is designed entirely for players with disabilities. *Polygon*. https://www.polygon.com/2018/5/17/17363528/xbox-adaptive-controller-disability-accessible
32. Story, M.F. and Mueller, J.L. (2011). Universal design of products. Chapter 32 in *Universal Design Handbook* (2nd ed.), W.F.E. Preiser and K.H. Smith (eds.). New York: McGraw-Hill, pp. 32.1-32.11. https://www.mhprofessional.com/universal-design-handbook-2e-9780071629232-usa
33. Sveistrup, H. (2004). Motor rehabilitation using virtual reality. *Journal of NeuroEngineering and Rehabilitation 1* (10). https://doi.org/10.1186/1743-0003-1-10
34. Sykownik, P., Graf, L., Zils, C. and Masuch, M. (2021). The most social platform ever? A survey about activities and motives of social VR users. *Proceedings of IEEE Virtual Reality and 3D User Interfaces (VR '21)*. Hoboken, NJ: IEEE Press, pp. 546-554. https://doi.org/10.1109/VR50410.2021.00079
35. Szalavári, Z. and Gervautz, M. (1997). The Personal Interaction Panel – a two-handed interface for augmented reality. *Computer Graphics Forum 16* (3), pp. 335-346. https://doi.org/10.1111/1467-8659.00137
36. Tzovaras, D., Nikolakis, G., Fergadis, G., Malasiotis, S. and Stavrakis, M. (2002). Design and implementation of virtual environments training of the visually impaire[d]. *Proceedings of the ACM Conference on Assistive Technologies (ASSETS '02)*. New York: ACM Press, pp. 41-48. https://doi.org/10.1145/638249.638259
37. Wobbrock, J.O., Gajos, K.Z., Kane, S.K. and Vanderheiden, G.C. (2018). Ability-based design. *Communications of the ACM 61* (6), pp. 62-71. https://doi.org/10.1145/3148051
38. Wobbrock, J.O., Kane, S.K., Gajos, K.Z., Harada, S. and Froehlich, J. (2011). Ability-based design: Concept, principles, and examples. *ACM Transactions on Accessible Computing 3* (3). Article No. 9. https://doi.org/10.1145/1952383.1952384

39. Zhang, K., Deldari, E., Yao, Y. and Zhao, Y. (2023). A diary study in social virtual reality: Impact of avatars with disability signifiers on the social experiences of people with disabilities. *Proceedings of the ACM Conference on Computers and Accessibility (ASSETS '23)*. New York: ACM Press. Article No. 40. https://doi.org/10.1145/3597638.3608388
40. Zhang, M.R., Zhong, M. and Wobbrock, J.O. (2022). Ga11y: An automated GIF annotation system for visually impaired users. *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '22)*. New York: ACM Press. Article No. 197. https://doi.org/10.1145/3491102.3502092
41. Zhao, Y., Bennett, C.L., Benko, H., Cutrell, E., Holz, C., Morris, M.R. and Sinclair, M. (2018). Enabling people with visual impairments to navigate virtual reality with a haptic and auditory cane simulation. *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '18)*. New York: ACM Press. Paper No. 116. https://doi.org/10.1145/3173574.3173690
42. Zhao, Y., Cutrell, E., Holz, C., Morris, M.R., Ofek, E. and Wilson, A.D. (2019). SeeingVR: A set of tools to make virtual reality more accessible to people with low vision. *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '19)*. New York: ACM Press. Paper No. 111. https://doi.org/10.1145/3290605.3300341