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Distance Perception in the Oculus Quest and Oculus Quest 2

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Distances in virtual environments (VEs) viewed on a head-mounted display (HMD) are typically underperceived relative to the intended distance. This paper presents an experiment comparing perceived egocentric distance in a real environment with that in a matched VE presented in the Oculus Quest and Oculus Quest 2. Participants made verbal judgments and blind walking judgments to an object on the ground. Both the Quest and Quest 2 produced underperception. Verbal judgments in the VE were 82% and 75% of the object distance, in contrast with real world judgments that were 94% of the object distance. Blind walking judgments were 68% and 70% of object distance in the Quest and Quest 2, respectively, compared to 88% in the real world. This project shows that significant underperception of distance persists even in modern HMDs.

Keywords: distance perception, depth perception, virtual reality, head mounted display, oculus quest, oculus quest 2, Blind walking, verbal report

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INTRODUCTION

In order for virtual reality (VR) to be fully effective, the accuracy with which distance is perceived in virtual environments (VEs) should be similar to that in real environments. However, distance in VR is consistently underperceived compared to the real world, especially when viewed through a head-mounted display (HMD) (Witmer and Kline, 1998; Thompson et al., 2004; Kelly et al., 2017). For example, a 2013 review of 33 studies found that distance in VR was perceived to be 73% of intended distance, on average (Renner et al., 2013) (also see Creem-Regehr et al. (2015a) for a review and synthesis).

Distance underperception in VR could have pervasive consequences for users. For example, real estate development stakeholders viewing a virtual walk-through of a planned structure (Ullah et al., 2018) will perceive the space to be smaller than intended, potentially leading to planning and decision errors. Likewise, a soldier learning to operate a vehicle or to coordinate spatially with other troops in VR will learn a set of perception-action associations based on underperceived distances, which might require recalibration in the real environment. Misperception of spatial properties of the VE can undermine their value by introducing costly errors associated with decisions and actions based on the misperceived environment.

The phenomenon of distance underperception in VR has been documented for more than two decades (Witmer and Kline, 1998; Witmer and Sadowski, 1998). However, HMD technology has evolved considerably since that time, and distance perception has also improved (Feldstein et al., 2020). The 2016 release of the Oculus Rift and HTC Vive ushered in a new era of consumer-oriented VR, and subsequent years have seen a proliferation of HMDs available to consumers. Compared with earlier HMDs, modern HMDs generally offer a larger field of view (FOV), higher resolution, greater pixel density, lighter weight, brighter displays, and improved ergonomics, not to mention dramatically lower cost. Newer HMDs provide more accurate distance perception when directly compared with older HMDs (Creem-Regehr et al., 2015b; Kelly et al., 2017; Buck et al., 2018), although there is some evidence that even newer HMDs produce underperception compared to real environments (Kelly et al., 2017).

Many studies have compared perceived distance in a VE with that in a matched real environment (Aseeri et al., 2019; Ding et al., 2020; Feldstein et al., 2020; Grechkin et al., 2010; Kelly et al., 2017; Peer and Ponto, 2017; Ries et al., 2008; Sahm et al., 2005; Thompson et al., 2004; Willemsen and Gooch, 2002; Willemsen et al., 2009). This comparison is particularly useful because it removes the assumption that real world distance perception is 100% accurate. Although distance judgments in real environments are often found to be around 100% of the target distance [see (Knapp and Loomis, 2004) for a review], they are occasionally somewhat lower (e.g., (Aseeri et al., 2019; Grechkin et al., 2010; Kelly et al., 2017; Peer and Ponto, 2017). Therefore, it is advisable that researchers hoping to contextualize the underperception of distance in VR also measure perception in a real environment. Although the dramatic underperception that characterizes some older VR headsets (Renner et al., 2013) is evident without a real world comparison, researchers using modern consumer-grade headsets commonly report distance judgments above 80% ((Ahn et al., 2021; Buck et al., 2018; Ding et al., 2020; Masnadi et al., 2021; Kelly et al., 2017; Zhang et al., 2021)). As distance perception in VR improves, real world comparison becomes more important to establish whether underperception still occurs.

There are currently no published data on absolute distance perception in the Oculus Quest or Oculus Quest 2 (but see (Arora et al., 2021) for an investigation of relative distance judgments in the Oculus Quest), which represent two of the most popular HMDs among consumers. The Oculus Quest and Oculus Quest 2 currently make up 4.4% and 39.6% of HMDs connected to Steam VR (https://store.steampowered.com/hwsurvey/; retrieved on 3 January 2022). These numbers likely underestimate the popularity of the Quest and Quest 2, since Steam VR requires a connection to a gaming-capable PC and many users are drawn to purchase the Quest and Quest 2 HMDs precisely because they can also operate as stand-alone consoles. Thus, the primary contribution of this paper is to present new data from a carefully controlled experiment comparing perceived egocentric distance in a real environment with that in a matched VE presented on the Oculus Quest and Oculus Quest 2. Participants viewed an object placed on the ground plane and made two types of egocentric distance judgments: verbal judgments and blind walking judgments.

The study design and hypotheses were pre-registered on the Open Science Framework: https://osf.io/hq5fp/. The primary independent variable was the viewing condition: real world, Quest, or Quest 2. The primary hypothesis was that distance perception would be more accurate in the real world compared to the Quest and Quest 2, based on research showing that perceived distance is typically less than 100%, even in modern displays (Aseeri et al., 2019; Buck et al., 2018, 2021; Creem-Regehr et al., 2015b; Ding et al., 2020; Kelly et al., 2017; Li et al., 2015; Peer and Ponto, 2017). Comparison between the two HMDs was exploratory, since it was unclear whether technical differences between the displays should affect perceived distance. Likewise, analysis of the effect of object distance was exploratory.

MATERIALS AND METHODS

Participants

The target sample size was 93 participants (31 per viewing condition), which was estimated by conducting a power analysis (G*Power v3.1) with the following parameters: independent samples comparison between two groups, Cohen's $d = 0.73$, alpha = 0.05, minimum power needed to detect an effect = 0.80. Effect size was based on the verbal judgment data in Kelly et al. (2017), who used a similar design and reported a significant difference between real and virtual viewing conditions (they reported no difference between conditions for blind walking judgments, so only verbal data were used to estimate effect size).

A total of 93 individuals participated in the experiment in exchange for a gift card. Thirty participants (15 men, 15 women; mean age = 20.27, *SE* = 0.35) experienced the real environment, 31 participants (17 men, 14 women; mean age = 21.23, *SE* = 0.53) experienced the Oculus Quest, and 32 participants (17 men, 15 women; mean age = 20.57, *SE* = 0.48) experienced the Oculus Quest 2. Participants were recruited through a mass e-mail to university students. To be eligible for the study, participants were required to be 18 years or older, able to walk short distances, have normal or corrected-to-normal vision, and without history of amblyopia (an imbalance between the two eyes that can lead to problems with stereo vision) or photosensitive seizures. Participants and experimenters were required to wear masks throughout the experiment.

Design

The study used a 3 (viewing condition: real world, Quest, and Quest 2) by 5 (object distance: 1, 2, 3, 4, and 5 m) mixed design. Viewing condition was manipulated between participants and object distance was manipulated within participants. Participants were assigned to the real classroom, Quest, or Quest 2 at the time of enrollment in the study. The real world condition was run first, followed by the Quest, followed by the Quest 2. All participants completed the study within a 1.5 month period. Participants completed two separate blocks of verbal distance judgments and blind walking distance judgments, and block order was counterbalanced. Each block consisted of 15 trials, corresponding to five egocentric distances (1, 2, 3, 4, and 5 m) repeated three times each in a random order that was held constant across all participants (i.e., the same random order was used for all participants).

Stimuli

The real environment was a university classroom, 9.3 by 9.17 m. Tables and chairs were moved to the sides of the room, allowing for an open walking space to perform the distance judgment task. The VE was experienced through the Oculus Quest or Quest 2.

Each HMD was modified by removing the stock elastic head strap and replacing it with the HTC Vive Deluxe Audio Strap using custom 3D printed parts to make the connections. This was done because the Deluxe Audio Strap is easier to sanitize than the stock head strap and because the ratcheting size adjustment on the Deluxe Audio Strap is easier for participants to use. A silicone cover was added to the stock HMD face pad. The silicone cover

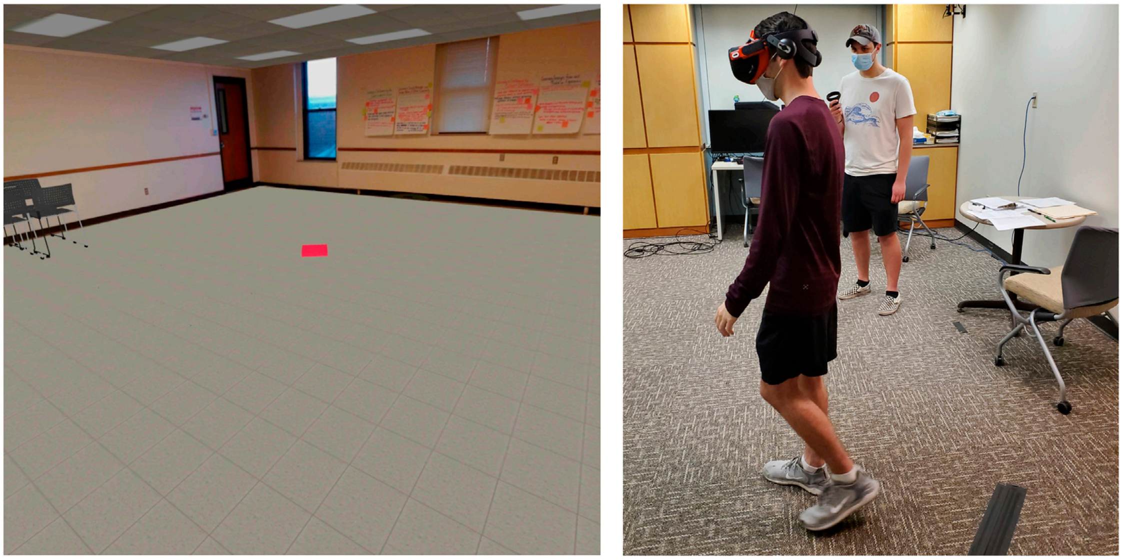

FIGURE 1 | Left: Screenshot of the virtual classroom taken from the position of the viewing location. The red square is the target object used for verbal and blind walking distance judgments. Right: Participant (foreground) and researcher (background) during a blind walking trial.

contained a nose flap that blocked some of the light entering from below the display, although some light leakage probably occurred for most participants.

The VE was built in Unity game engine, and was designed to mimic the real classroom (see **Figure 1**, left). Photographic textures obtained from the real classroom were used for most surfaces, and spatial properties of the room and its contents were carefully matched. The VE was experienced while standing within a 6 by 7 m research lab (see **Figure 1**, right). The virtual environment did not contain shadows cast by virtual objects, nor did it include an avatar representing the participant's body.

The target object was a red square, 18 by 18 cm, placed on the floor of the environment. In the real classroom the target was made out of red cardboard. The viewing location in the real environment was marked by a strip of black tape on the floor, near the corner of the room. A similar black strip also appeared in the VE. The lab room in which the virtual conditions took place contained a raised rubber pad on the floor corresponding to the location of the virtual tape strip, so that participants could feel when they were standing at the viewing location.

A laser distance measure was used to measure walked distance on blind walking trials.

Procedure

Upon arrival at the research site, the participant completed the informed consent form as well as a COVID-19 screening form. The researcher then provided a basic description of the verbal and blind walking judgments.

In order to remind the participant of standard units of measurement used when making verbal judgments, the researcher led the participant into the hallway outside the classroom/lab to view tape markings on the floor corresponding to 1 foot and 1 m. The participant was given the choice of which measurement unit to use when making verbal distance judgments.

All distance judgments began with the participant standing at the viewing location with toes placed on the black tape. On blind walking trials in the real environment, the participant was instructed to close their eyes while the researcher placed the target object at the appropriate egocentric distance (faint marks guided the researcher but were not visible from the participant's perspective). The researcher then instructed the participant to open their eyes. After 5 s of viewing, the participant closed their eyes, the researcher picked up the object, and the participant was instructed to walk to the previously seen object location with eyes closed.

Blind walking trials in the VE were similar to those in the real environment, except the timing of object presentation was controlled through the software, and the display turned uniformly black at times in which the participant was expected to close their eyes.

Regardless of environment (real or virtual), the researcher then measured and recorded walked distance. Measurement was accomplished with a laser measure positioned at the viewing location and aimed at the heel of the participant's shoe. Walked distance was recorded in meters.

The procedure for verbal trials was similar to that for blind walking trials, except that the participant was instructed to verbally report the distance from their standing location to the location of the object, and the researcher recorded the judgment. Verbal judgments made in imperial units were later converted to metric units.

RESULTS

Prior to analysis, judged distance was converted to a ratio of judged distance relative to object distance. Verbal judgment ratios

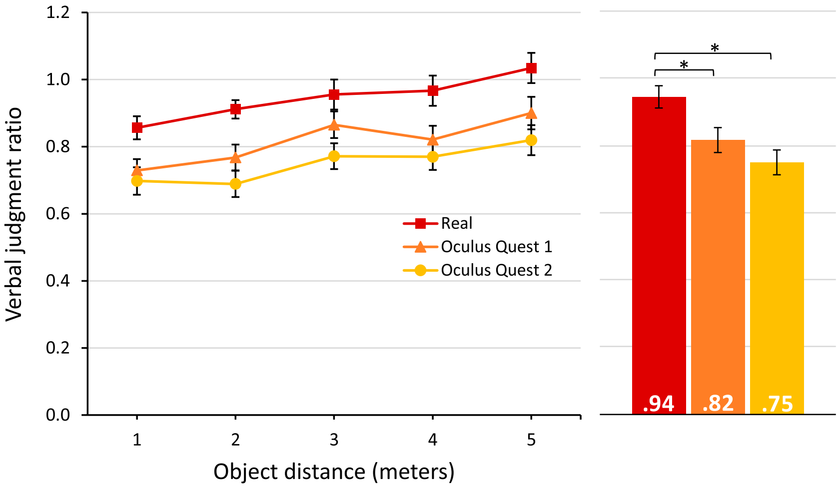

FIGURE 2 | Average verbal distance judgments expressed as a ratio of object distance. Data are plotted as a function of object distance (line graph, left), and also averaged across object distance (bar graph, right). Error bars represent ± one SEM. *p <0 .05.

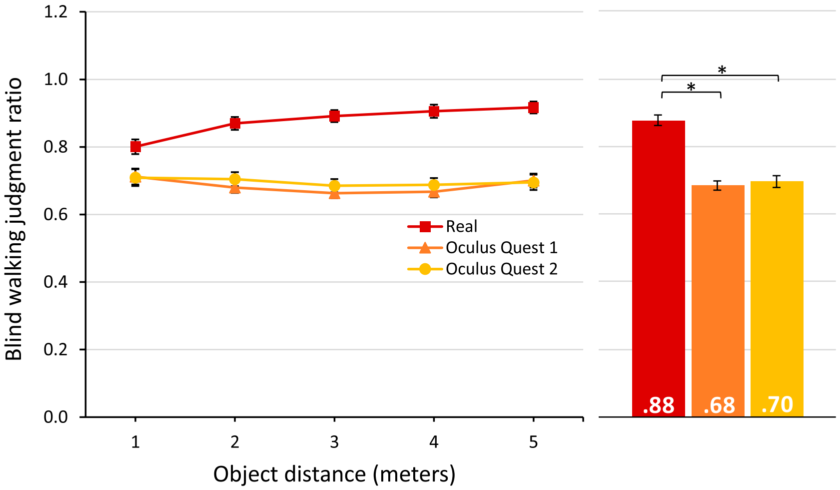

FIGURE 3 | Average blind walking distance judgments expressed as a ratio of object distance. Data are plotted as a function of object distance (line graph, left), and also averaged across object distance (bar graph, right). Error bars represent ± one SEM. *p <0 .05.

are presented in **Figure 2** and blind walking judgment ratios are presented in **Figure 3**.

Verbal and blind-walking data were analyzed separately in 3 (viewing condition: real, Quest, or Quest 2) by 5 (object distance: 1–5 m) mixed-model ANOVAs. For verbal judgments, Mauchly's test of sphericity was violated for the object distance variable so the analysis proceeded using a Greenhouse-Geisser correction. The main effect of viewing condition was significant, F (2, 90) = 7.749, $p = 0.001$, $\eta_p^2 = 0.147$. Tukey post-hoc tests were used to evaluate the primary hypothesis that verbal distance judgments would be more accurate in the real environment compared to the Quest and Quest 2. Verbal distance judgments in the real environment ($M = 0.945$, $SD = 0.223$) were significantly more accurate than verbal judgments in the Oculus Quest ($M = 0.817$, $SD = 0.232$), $p = 0.036$, as well as the Quest 2 ($M = 0.748$, $SD = 0.234$), $p = 0.001$. Verbal judgments in the Quest and Quest 2 did not differ significantly from one another, $p = 0.377$. The main effect of object distance was significant, F (2.19, 197.18) = 26.084, $p < 0.001$, $\eta_p^2 = 0.225$: verbal judgment ratios increased as a function of object distance, confirmed by a significant linear contrast, F (1, 90) = 40.242, $p < 0.001$, $\eta_p^2 = 0.309$. There was not a significant interaction between object distance and viewing condition, F (4.38, 197.18) = 0.714, $p = 0.595$, $\eta_p^2 = 0.016$.

For blind walking judgments, Mauchly's test of sphericity was violated for the object distance variable, so the analysis proceeded using a Greenhouse-Geisser correction. The main effect of viewing condition was significant, F (2, 90) = 45.232, $p < 0.001$, $\eta_p^2 = 0.501$. Tukey post-hoc tests were used to evaluate the primary hypothesis that blind walking distance judgments would be more accurate in the real environment compared to the Quest and Quest 2. Blind walking judgments in the real environment ($M = 0.877$, $SD = 0.111$) were significantly more accurate than blind walking judgments in the Oculus Quest ($M = 0.685$, $SD = 0.104$), $p < 0.001$, as well as the Quest 2 ($M = 0.689$, $SD = 0.134$), $p < 0.001$. Blind walking judgments in the Quest and Quest 2 did not differ significantly from one another, $p = 0.861$. The main effect of object distance was not significant, F (2.56, 230.04) = 2.442, $p = 0.075$, $\eta_p^2 = 0.026$. There was a significant interaction between object distance and viewing condition, F (5.11, 230.04) = 4.815, $p < 0.001$, $\eta_p^2 = 0.097$. Contrasts showed that judgments in the real environment contained significant linear, F (1, 29) = 31.691, $p < 0.001$, $\eta_p^2 = 0.522$, and quadratic trends, F (1, 29) = 9.746, $p = 0.004$, $\eta_p^2 = 0.252$: as object distance increased, distance accuracy increased most between 1 and 2 m and then increased more gradually for subsequent distances. Judgments in the Quest contained a significant quadratic trend, F (1, 30) = 7.520, $p = 0.010$, $\eta_p^2 = 0.200$: as object distance increased, distance judgment ratios initially decreased slightly and later increased slightly. Judgments in the Quest 2 contained no significant trends as a function of object distance, although the visual pattern is similar to that found in the Quest.

DISCUSSION

Egocentric distance in a VE presented on the Oculus Quest and Oculus Quest 2 was underperceived relative to intended object distance, and also relative to perceived distance measured in a real environment upon which the VE was based. Evidence of underperception in both HMDs was found in verbal distance judgments as well as blind walking distance judgments. There were no significant differences between judgments made in the Quest and Quest 2.

The pattern of distance judgments as a function of object distance varied across response modality. Verbal distance judgment ratios increased linearly with object distance, regardless of viewing condition. Blind walking distance judgment ratios in the real environment also increased as a function of object distance (albeit non-linearly), but were mostly flat in the Quest and Quest 2, leading to a spreading interaction. The distinct patterns across the two dependent variables may reflect reliance on different distance cues. Whereas blind walking judgments are heavily dependent on angular declination of the target relative to the horizon (Ooi et al., 2001; Messing and Durgin, 2005), verbal judgments may depend more on contextual cues that help to scale the relevant units used in the verbal response.

The VE used in this study lacked shadows cast by virtual objects, although the photographic wall textures did contain shadows. Shadows are particularly useful for indicating contact between objects and surfaces, such as the ground plane (Hu et al., 2000; Madison et al., 2001; Adams et al., 2021). The target object used in this study was flat and flush with the floor, but future studies may benefit from using a 3D object (e.g., a sphere) that casts shadows on the ground plane.

Perceived distance in the Oculus Quest and Oculus Quest 2 ranged from 68 to 82% of intended distance, depending on the specific HMD and the response modality, and averaged 74% across the two HMDs and the two response types. Although averaging across response modalities is not typical, it provides an overall value with which to compare to the 73% value representing judged distance combined across several studies reviewed by Renner et al. (2013). The lack of clear improvement in the Quest and Quest 2 compared to older displays reported by Renner et al. (2013), despite vast technological advancements in recent years, is concerning and suggests that further improvements in HMD technology (e.g., wider field of view, higher resolution, etc.) may not resolve the underlying causes of distance underperception. The similarity in distance judgments when using the Quest and Quest 2 further underscores the concern that technological advances may not foster better distance perception. Although there are many technological differences between the Quest and Quest 2, the most salient is the difference in resolution (1,440 by 1,600 in the Quest and 1832 by 1920 in the Quest 2). The current results suggest that resolution is not the limiting factor, corroborating similar conclusions from other research (Willemsen and Gooch, 2002; Thompson et al., 2004; Buck et al., 2021).

There is a growing body of data on perceived distance using other modern consumer-grade HMDs, most notably the HTC Vive and the Oculus Rift (the consumer version, to distinguish from earlier development kits). Studies using the HTC Vive report distance judgments ranging from 66% (Buck et al., 2018) to 102% (Zhang et al., 2021) of actual distance, with several studies reporting intermediate values (Aseeri et al., 2019; Kelly et al., 2017; Maruhn et al., 2019; Peer and Ponto, 2017). Studies using the Oculus Rift report distance judgments from 75% (Peer and Ponto, 2017) to 104% (Ahn et al., 2021) of actual distance, with many in between (Aseeri et al., 2019; Buck et al., 2018; Ding et al., 2020). In this context, the current results from the Oculus Quest and Oculus Quest 2 are on the low end of the range established for other consumer-grade HMDs. Technological differences that would seem to favor the Quest and Quest 2 over the Oculus Rift and HTC Vive include the wireless capability of the Quest and Quest 2 compared to the typically tethered experience provided by the Rift and Vive, and the higher resolution of the Quest (1,440 by 1,600 pixels) and especially the Quest 2 (1,832 by 1,920 pixels) compared to the Rift (1,080 by 1,200 pixels) and Vive (1,080 by 1,200 pixels). On the other hand, the diagonal FOV of the HTC Vive (approximately 148°) is superior to that of the Quest (approximately 130°), Quest 2 and the Oculus Rift (both approximately 134°). The HMD weights are all very similar and much lighter than earlier displays, although the Quest (571 g) is slightly heavier than the Quest 2 (502 g), Oculus Rift (470 g), and HTC Vive (555 g). In terms of technical specifications, there is no clear reason why the Quest and Quest 2 would produce distance perception on the low end of the ranges established by the HTC Vive and Oculus Rift.

Although modern HMDs such as the Oculus Quest and Oculus Quest 2 continue to cause underperception of egocentric distance, research has identified several techniques that can be leveraged to alleviate the problem. Recalibration by walking through the VE improves blind-walking judgments (Kelly et al., 2014, 2018; Richardson and Waller, 2007; Waller and Richardson, 2008) as well as size judgments (Siegel and Kelly, 2017; Siegel et al., 2017), albeit to a lesser extent, although it can also cause miscalibration of actions subsequently performed in the real world (Waller and Richardson 2008). The widespread availability of room-scale tracking makes recalibration by walking trivial: simply walking around and exploring on foot, which naturally occurs in most VEs, leads to recalibration equivalent to more carefully controlled recalibration procedures (Waller and Richardson, 2008). Providing a self-avatar improves perceived distance (Aseeri et al., 2019; Leyrer et al., 2011; Ries et al., 2008), perhaps by providing additional familiar size cues. Displaying a replica of the actual environment in which the user is located also improves perceived distance (Interrante et al., 2006; Kelly et al., 2018), and this improvement may carry over into novel VEs (Steinicke et al., 2009). For simulations in which perceived distance is important, these tools remain the best ways to improve perceived distance until HMD technology supports perception of spatial properties on par with the real environments they intend to represent.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: Open Science Framework: https://osf.io/hq5fp/.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Iowa State University Institutional Review Board. The patients/participants provided their written informed consent to participate in this study. Consent was obtained from the researchers for the publication of their images in this article.

AUTHOR CONTRIBUTIONS

The research was conceptualized by JK, TD, MA, and LC. MA coded the experiment. TD supervised data collection and analyzed the data. JK drafted the paper. TD, MA, and LC provided feedback and revisions on the paper.

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