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A Pilot Study of Assessing Visual Hallucinations using Virtual Reality in Lewy Body Disorders

Running Title: VR for VH in LBDs

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Abstract

Visual hallucinations (VH), defined a visual perception without a corresponding object in the visual environment, are characteristic of Lewy body disorders and associated with adverse outcomes. Clinical management remains limited by reliance on retrospective self-report and challenges distinguishing between various visual experiences. We piloted a structured virtual reality (VR) environmental exposure protocol to systematically characterize abnormal visual perceptual events. Participants were exposed to four environments under varying visual conditions and narrated their experience. Narratives were independently reviewed by two clinicians for abnormal visual perceptive events.

Eleven participants with Parkinson's disease or dementia with Lewy bodies (6 VH+, 5 VH− by questionnaire) completed the protocol. Across participants, 23 abnormal perceptual events were identified (6 hallucinations, 17 misperceptions). Event phenomenology aligned with clinical descriptions and occurred more frequently during visually degraded conditions. Perceptual error events were observed more frequently in VR than typically captured through retrospective interview (2.09 vs 0.016 per participant). However, event rates did not differ significantly between VH+ and VH− groups and did not replicate participants' typical spontaneous hallucinations. Technical and methodological constraints further limit interpretation.

These findings demonstrate the feasibility and tolerability of structured VR-based assessment of perceptual vulnerability in Lewy body disorders and support further development and validation of this approach.

Background

Visual hallucinations (VH) are defined as visual sensory perceptions without external corresponding visual stimuli. VH are a prototypical feature of Lewy body disorders (LBD)s such as Parkinson's disease (PD), Parkinson's disease dementia (PDD), and Dementia with Lewy bodies (DLB), and are thought to happen in up to 40-60% of those with PD [1, 2]. In LBDs individuals prototypically report repeatedly seeing animals or people who are not there for seconds to minutes. VH are also coincident with other neuropsychiatric symptoms [3, 4], dementia [5], and increase the risk for nursing home placement [6]. The presence of VH in PD significantly impacts treatment, resulting in the addition of antipsychotic medications that increase the risk of death [7] or in reduction of quality of life by withdrawal of dopaminergic medications [8, 9].

However, determining if VH are present is challenging as it fundamentally relies on the summative historical report of patients. Usually, these reports are obtained from clinical interviews during clinical encounters, but sometimes questionnaires and/or scales are used [10, 11]. Whichever method is used, all struggle to differentiate VH from objectively valid perceptions (reality) or from inaccurate perceptions based on visual stimuli (misperceptions, MP). Furthermore, cognitive impairment and stigma against reporting psychosis are likely to further reduce the reporting rates of current assessments. Differentiation becomes easier when caregivers or collateral information are present, but ambiguity often remains, and uncertainty exists on whether there is a clinically meaningful difference between VH and MP. Given the established significance of VH on individuals with LBDs and the weaknesses of current methodologies of assessing VH, there is a need for tools to improve understanding, characterization, and decision making around VH.

Virtual reality (VR) devices can address these issues by unlocking an unparalleled means of controlling visual sensory input and recording responses. Studies in healthy individuals using VR generated environments have been used to simulate visual hallucinations [12, 13]. In PD, VR has been rarely associated with simple hallucinations and were predictive of future visual hallucinations [14]. VR has also been used to facilitate tactile and presence hallucinations in individuals with PD [15]. Synergistically, virtual reality devices can be paired with eye movement tracking (EMT) technology to assess visual system function. Previous studies have used EMT in PD and DLB to show abnormal oculomotor and visuospatial function, including

saccade abnormalities, longer fixation periods, reduced breadth of visual search, and increased reliance on perceptual priors [16-18]. However, more pertinently for VH eye tracking can be used to determine where an individual's visual focus is in the environment and thereby help identify what visual stimuli is contributing to visual perception [19]. In pareidolia, a phenomenon thought to be related to VH where ambiguous stimuli are interpreted as meaningful eye tracking has been utilized to quantify changes in fixation durations and locations that are associated with clinical pareidolia [20].

However, to our knowledge, there has not been an in-depth evaluation of the ability of virtual reality environments combined with eye tracking based visual focus and visual stimuli identification to objectively characterize perceptive abnormalities. The combination of these technologies, which allow for an unparalleled understanding of visual stimuli, with real-time verbal narratives of patient perception should allow for objective characterization of hallucinations and misperceptions. The development of such a methodology would theoretically allow for the controlled, reliable, and objective assessment of visual perceptual abnormalities in real time, which would increase our ability to understand the context in which visual hallucinations occur and support therapeutic interventions.

Given this, we sought to pilot the use of such a methodology in individuals with PD, PDD, or DLB with and without clinically established visual hallucinations. We hypothesized this methodology would capture events in the lab at a rate greater than expected by subjective report, given that subjective report would be negatively biased due to recall limitations and by the visual setting typical of clinic and lab environments. Furthermore, if event rates were not higher than subjective report, there would be very little reason to use this methodology as one would gain a similar amount of information just from observation alone. Additionally, we wanted to ensure that the VR events we were capturing were related to the clinical phenomena we sought to understand. Therefore, we hypothesized that those with visual hallucinations as determined by the current reference standard (structured clinical interview-based scale) would have a higher rate of events in VR than those without.

Methods

Study design

We conducted a proof-of-concept single-time point observational study. Inclusion criteria were as follows: 1) clinically established or probable PD as defined by the 2015 MDS Consensus criteria OR probable DLB as defined by the fifth consensus criteria 2) able to provide informed consent 3) able to speak and read English. Exclusion criteria were as follow: 1) psychologically high risk (experiencing severe distress from their VH or history of suicidality) or had a prior confounding psychiatric factor (diagnosis of primary psychiatric disorder with history of hallucinations or substance use disorder 2) severe dementia limiting ability to follow directions 3) pregnancy 4) inability to use controllers 5) ophthalmoplegia 6) functional blindness (mono or binocular) 7) significant uncorrected hearing loss 8) scalp/skull deformities.

Participants were initially defined as having a history of VH based on questionnaire responses adapted from the PsychQ scale [21]. If a participant responded yes to "See shadowy forms that aren't really there?", "Mistake an object for something else e.g. a snake instead of a hose?", or "See people or things (e.g. animals) that aren't really there?" relating to the last year they were categorized as having VH (VH+), otherwise they were labeled as not having VH (VH-).

The study and all experimental protocols were approved by the University of Washington Institutional Review Board (STUDY00019774). The study and all methods were conducted in accordance with the Declaration of Helsinki and followed all relevant guidelines and regulations. Informed written consent was obtained from all participants before study assessments were performed. Participants were recruited from the University of Washington clinics and from affiliated registries from September of 2024 to January of 2025 during the primary investigators fellowship training period. Recruitment of 10 VH+, 10 VH-, and 10 age matched controls was planned.

Assessment Visit

The study visit consisted of an initial clinical assessment during which demographic and disease related information was collected - age, gender, diagnosis, years since diagnosis, years since onset of VH, and years since onset of cognitive symptoms. A current list of neurologic medications (anti-parkinsonian medications, anti-epileptics, anticholinergics, memantine, anti-psychotic medications, stimulants, anti-depressants, and any other medication with significant cognitive side-effects) was also collected.

Validated questionnaires and clinical exams included the PsycH-Q, Scale for the Assessment of Positive Symptoms, PD Version (SAPS-PD) [22], the Movement Disorders Society Unified Parkinson's Disease Rating Scale (MDS-UPDRS, Part I, II, and III) [23], and the MoCA [24, 25]. We also conducted a semi-structured interview assessing visual hallucinations which was adapted from the North-East Visual Hallucinations Interview [11]. This interview encompassed all components of the scale but added additional questions to collect further details about participant experiences with VH with a focus on the quality, emotional valiance, temporal characteristics, triggers, and associations with other symptoms (Supplementary – NEVHI modified). Clinical data was collected and stored within REDCap. The clinical assessment was followed by the virtual reality assessment protocol which last for about 45 minutes and was split into a calibration and acclimation phase followed by an induction phase. During the VR protocol, participants wore an HTC VIVE Focus 3 with an add on HTC VIVE Focus 3 Eye Tracker that was embedded into the headset (Supplementary - Figure 1). The VR device was not connected to a computer and ran in standalone mode. Participants were seated and guided through the VR protocol by a study researcher. Finally, at the end of the study participants answered questions summarizing their visual experiences and providing study related feedback. These responses were collected using a self-administered questionnaire with study clinician support available if questions responses were unclear or questions were felt to be ambiguous (Supplementary – End of study questionnaire) (Figure 1A).

VR Protocol: General design and implementation

Given that visual hallucinations have been reported to occur more under dark, low light conditions with ambiguous stimuli [2] and based on the perception and attention deficit model [26], the focus of our protocol was to create environmental conditions with poor sensory activation and contextual clues in VR. Using the Unity game engine (Version 2022.3.37f1), we developed a VR research assessment program/game in house from various VR development assets and game assets in the Unity asset store (Supplementary – Asset List). Unity and HTC provided assets were utilized and integrated into our program to record visual fixation location as well as controller and headset locations in the virtual environment. The recorded logging rate was generally around 50 Hz. Additionally, all visual input and audio output were recorded for later review using the screen recording feature present in the headset.

We decided to separate the VR evaluation into an initial calibration and acclimation phase followed by an induction phase. In the calibration phase, we wanted to ensure participants were tolerating the environment, able to navigate in VR, and that motion tracking was working as expected. Then in the induction phase, we wanted to cycle through various visual environments while varying clarity and lighting so as to evaluate whether visual perceptual abnormalities occurred. In order to ensure the experience was comparable between calibration and induction, we copied the same pattern of environmental effects for both phases (Figure 1A).

The entire VR protocol was done without auditory cues or other purposefully generated sound.

VR Protocol: Scene and stimuli selection

For the induction phase, we selected scene environments and targets with the intention to obtain a wide variety of visual and contextual features. For scene environments and targets, the features we were interested in representing were both well-defined and ambiguous environments, natural and human constructed environments, and simple and complex environments. We then looked for these game objects in the Unity asset store and based on the availability of free or low-cost assets we obtained and integrated these into our protocol.

Unfortunately, given the need to limit the duration of testing, the processing power of the headset, and the effort required for successful asset integration we down selected our induction environments to only a core set of four which we believed still reasonably captured the diversity that we were originally interested in creating.

We selected a room environment which represented a simple, contextually well-defined, and human constructed environment. Our second environment was a forest environment which represented a simple, low poly, contextually well-defined, and nature-like environment. Our third environment was a science station environment which represented a complex, contextually poorly defined, and human constructed environment. Our fourth environment was a city environment which represented a complex, contextually well-defined, and human constructed environment (Figure 1C).

Similarly, we selected a set of target objects which were a mix of objects native to the various environments and new objects obtained from packages not related to the presented environments (Figure 1B4). We sought to utilize a diverse set of objects with variable visual features such as complexity and

ambiguity. For target objects, we selected 15 total objects as this is the count frequently utilized by many validated memory based assessments [27].

VR Protocol: Calibration and acclimation

The first environment was focused on developing comfort with visually exploring and navigating using the VR device. It was a basic room in which participants practiced moving and interacting with the virtual environment using the controllers and using the headset to look around (Figure 1B.1). The second environment was designed to practice a simple goal directed behavior (visually guided prosaccades). Participants in this environment were placed in an open plane in which a spherical target appeared randomly within a defined grid at set time intervals. Participants were asked to look at the target without moving their head (Figure 1B.2). The third environment was a control and training environment designed to evaluate the ability of participants to identify and name a target set of objects which would be used in the induction environments to come. The environment consisted of three pedestals, a floor, and a background. In this environment, objects were presented above the pedestals (Figure 1B.3). For each object (Figure 1B.4), participants were asked to look at it, name it, point the controller at it, and delete it by clicking on it. If an area above a pedestal was empty a new object would be created until all objects within the set were created. The fourth and final environment was a black environment designed to evaluate light leakage or other visual perceptual abnormalities in the relative absence of stimuli. The four calibration environments were presented a total of four times with the various visual effects (Figure 1A).

VR Protocol: Induction phase, general

After completing the calibration phase participants would move to the induction phase. For this phase, we instructed participants to visually explore the environments and asked them to name all the objects they saw. We emphasized that they should provide additional details if they felt an object was unusual or experienced something that was reminiscent of prior VH. Participants were able to navigate the environments with the joysticks of the controllers and were encouraged to do so but this was not required.

During the induction procedure, participants were brought into the four selected induction environments, each of which was presented for one minute. This sequence of environments was then repeated for each of our four visual effect conditions again in a set sequence going from more visible to less (Figure 1A).

In each environment, a random subset of the target objects from the calibration trials would appear near the participant. These would appear at a random location and would occur one at a time every few seconds during the period the environment was active. These would remain present until the next environment was presented but could be removed by the participant. Participants were not instructed to hunt for these objects or given additional instructions related to these objects. The total time of the induction phase was 16 minutes.

VR Protocol: Objective review

The virtual reality assessment was monitored by a study researcher who watched the screencast of the experience in real time and noted any verbal descriptions not consistent with what was present. Additionally, the researcher would ask additional questions if an inconsistent description was given. After the assessment, screen, eye-tracking, and audio recordings were reviewed by a study team clinician (SH) for events where atypical verbal descriptions were provided for visual elements. Review of atypical events was assisted by using a software tool that allowed recreation of the scenes by using stored eye tracking and location data (Supplementary Figure 2). Events were then classified into either misperceptions or visual hallucinations. Flagged events were then independently confirmed by a second study clinician (YL). If there was a disagreement between raters, then the event was discussed and classified based on consensus or removed. For ratings, we defined misperceptions as events in which verbal description of a visual stimuli was inappropriate despite the object being discernible to the reviewer and discernible to the participant during calibration trials, and we defined visual hallucinations as an event in which the raters were clearly able to understand the verbal description provided but were unable to attribute the description to a visual stimulus in the foreground.

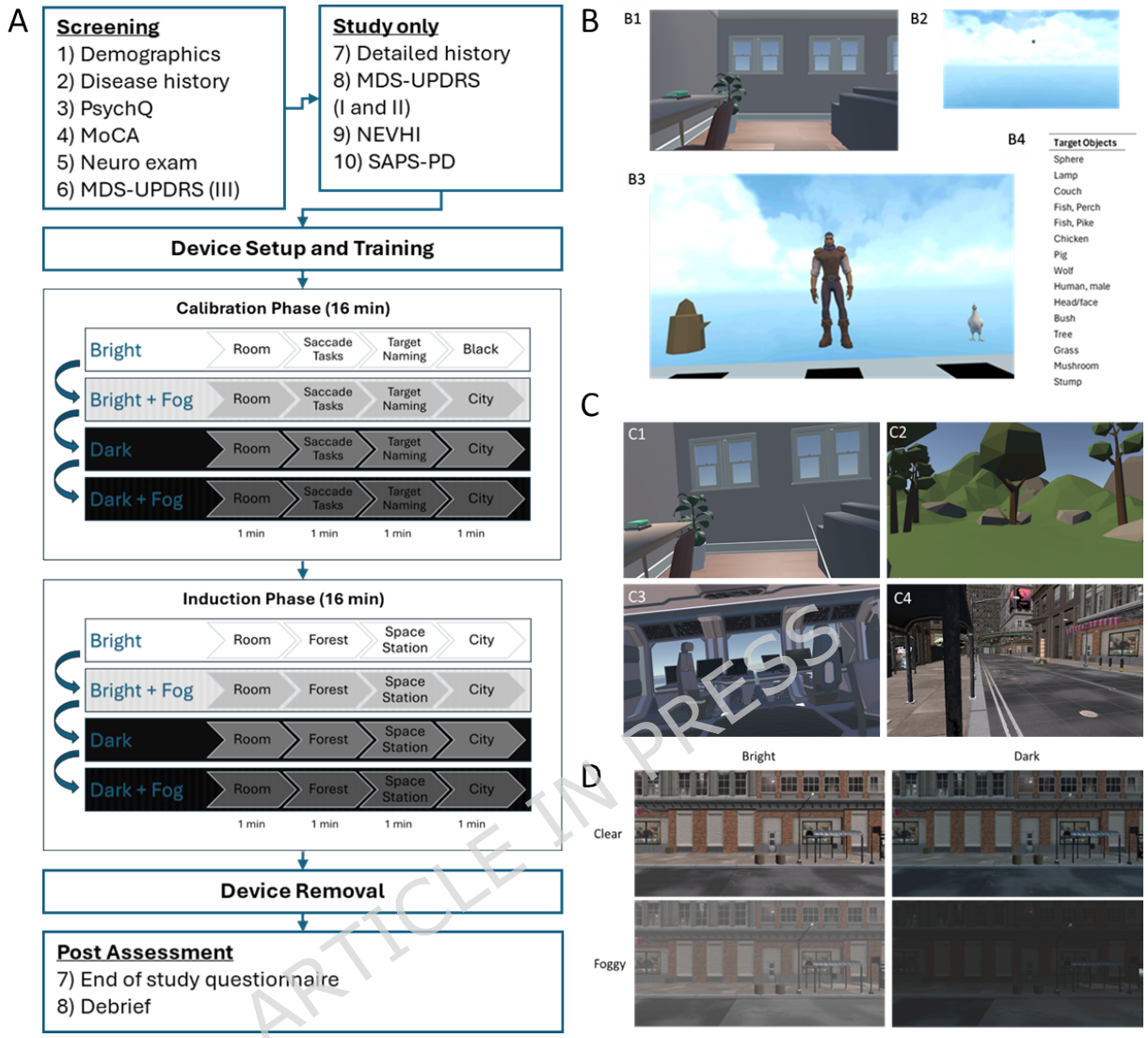

Figure 1. Study Protocol and Design. A) Study outline. Events usually occurred in number order. The VR phases would start with the bright condition and the room environment then continue to the rest of the environments before restarting the cycle with a new visual effect. B) VR calibration phase environments. Representative screenshots. B1) Practice room. B2) Saccade environment. B3) Naming environment B4) list of target objects displayed in this environment. C) VR induction phase environments. Representative screenshots. C1) Room environment. C2) Forest environment. C3) Space station environment. C4) City environment. D) Visual effects. Representative screenshots of the city environment with each visual effects.

Statistical Analysis

Participant characteristics and event rates were summarized descriptively. The expected event rate for VH was calculated based on the frequency of visual hallucinations over the last month (30 days) as reported during our modified NEVHI of the event rate reported during the last month. These values were scaled to 18 hours of daytime to remove periods of sleep.

Differences between groups were assessed using the exact Wilcoxon rank sum test (one-sided) to evaluate whether counts of events were higher in those with a history of VH as compared to those without. Effect size was quantified using Cliff's Delta with 95% confidence intervals to provide additional context on the magnitude of the difference.

Results

Participant characteristics

We screened 12 candidates and enrolled 11 participants (PD 10, DLB 1). All PD participants were without historical diagnosis of dementia. Of the 11 participants, six met our questionnaire-based definition of having history of VH with the single DLB participant in the VH+ group. Demographic and disease state characteristics were summarized descriptively (Table 1). Only one VH+ participant was on an acetylcholinesterase and no participants were on antipsychotics.

	VH+ (n = 6)		VH- (n = 5)	
	Mean	SD	Mean	SD
Age (years)	64.17	8.9	67.4	6.7
Gender (% Male)	100%		100%	
Time Since Diagnosis (years)	4.8	4.1	6.4	2.2
Duration of Motor Symptoms (years)	6.4	3.8	8.6	2.6
Duration of Cognitive Symptoms (years)	2.8	2.0	0.5	0.9
Duration of Visual Hallucinations (years)	2.2	1.8	-	-
LEDD*	534	454	635	238
MoCA	25.7	2.0	28.0	1.6
MDS UPDRS-I	18.3	5.9	7.4	4.7
MDS UPDRS-II	13.2	4.1	6.2	1.8
MDS-UPDRS-III	24.7	5.9	20.0	8.9

Table 1. Participant demographic and disease characteristics. LEDD: Levodopa equivalent daily dose. MDS UPRDRS: Movement Disorder Society Unified Parkinson's Disease Rating Scale MDS-UPDRS part III scoring was performed in the practical on state without request for medication hold or specific timing in relation to timing of medications. *LEDD was not calculable for 2 participants in each group.

Subjective historical report on visual hallucinations and abnormal perceptions

On our modified NEVHI, three of our six VH+ participants reported descriptions consistent with typical complex visual hallucinations, but the other three were uncertain due to the possibility of events being explained by natural phenomena, other neurologic phenomena (migraine aura for participant 7), or uncertainty of recall with conflicting or ambiguous responses to questions. Additionally, one participant who was initially assigned to the VH- group based on the modified PsychQ reported possible visual perceptual abnormalities (Table 2, Supplementary Table 1).

The event rate for visual hallucinations was estimated at 10 per month based on the subjective report of participants 1,4, and 6 as they were the only ones who reported any level of hallucinations in the last month. Assuming a uniform distribution, the expected rate of visual hallucinations would be approximately 0.016 events per participant during a 16-minute period, based on the subjective monthly reports.

	NEVHI Questions Basic				Clinical summary of features present	
ID	Eyes play tricks?	Seen what others could not?	Visual hallucinations?	Other visual experiences?	Simple VH	Complex VH
VH+						
1	Yes	Yes	Yes	Yes	No	Yes
4	Yes	Yes	Yes	Yes	Yes	Yes
6	Yes	Yes	Yes	Yes	Yes	Yes

7	No	Yes	Yes	Yes	Yes	Possible
10	Yes	No	No	Yes	No	Possible
11	Yes	No	No	No	No	Possible
VH-						
2	No	No	No	No	No	No
3	No	No	No	Yes	No	No
8	No	No	No	No	No	No
9	No	No	No	No	No	No
12	No	No	No	No	No	No

Table 2 – VH Interview responses and summary determinations by research team.

Subjective recall of virtual reality based hallucinations and perceptive abnormalities

Subjective recall by participants at the end of the study as assessed by questionnaire was notable for one participant having an experience that mimicked his visual hallucinations. Two other participants provided a positive response to the catch all question “Did you at any point while in VR see anything that you felt was not part of the game or coming from the screen?”. These responses were distributed between the groups. For participant 4 with history of VH, he reported “twig number changed between scenes”, “rain became snow”, and “the motor became a grate later” all of which were objectively unchanged in the environments. For participant 8 with PD and no history of VH, he reported a small floater in his right eye. None of our participants reported experiencing their typical VH in VR.

Objective review of virtual reality based hallucinations and perceptive abnormalities

Eye-tracking augmented review by the research team identified 23 events of abnormal perception, 17 misperceptions and 6 visual hallucinations (Table 3, Supplementary Table 2). The observed VR protocol event rate was 2.09 events per participant which markedly contrasted with the expected rate of 0.016 events per participant.

Both VH and MP were more common among the VH+ group, VH 0.67 vs 0.4 ($p = 0.44$) and MP 2.17 vs 0.8 ($p=0.11$) (Table 4, Figure 2), however even

when considered together as events of abnormal perception this did not reach statistical significance (p=0.11) though the effect size was estimated to be large but with a high degree of uncertainty, 0.53 (95% CI,-0.20 to 0.88).

Events occurred more commonly in the dark (78%) and equally between fog and clear conditions. Events were also more common in the forest and city environments with each having 39% of the events.

The most prominent event was a misperception of delusional quality which participant 1 experienced. This event occurred in our forest during the dark condition (Figure 3, Supplementary video S1, Supplementary video transcripts). At the time, he reported he briefly saw a hanging woman and felt disconcerted by this image. On further questioning he reported that this event was like experiences he had in the past. Notably, these earlier descriptions had been labeled clinically as visual hallucinations. Participant 10 had two similar notable experiences, both in the city scene in which he reported seeing movement that he attributed to cars or cyclists despite no concrete stimuli in the foreground and only an uncertain but possible relationship with light flickering in the background (Supplementary video S2 and S3, Supplementary video transcripts).

ID	Timing	Environ	Lighting	Clarity	Description of Phenomena	Label
VH+						
1						
	5:18	City	Bright	Clear	Pig is initially called a bear, then later "or a pig"	MP
	10:46	Forest	Dark	Clear	A branch/twig is labeled a shoe and later relabeled correctly as a "piece of wood"	MP
	11:22	Forest	Dark	Clear	Wolf is labeled a cheetah and then later he asks "what is that"	MP
	15:09	Forest	Dark	Fog	Tree looks like a hanging woman/person for a second. It looks like it could have a head there.	MP
4						
	7:20	City	Bright	Fog	Sees snow on the ground.	MP
	10:53	SciFi	Dark	Clear	Sees grating that previously he thought was a boat engine but is now clearly grating	MP
	11:33	City	Dark	Clear	Sees a wiggly thing that he doesn't know what to make of that, amorphous blob	VH

7						
	11:28	City	Dark	Clear	Sees raining on the street.	VH
	13:45	Forest	Dark	Fog	Sees a white tag instead of a mushroom.	MP
10						
	29:20	Forest	Bright	Clear	"I don't know, some of it could be sand." While reviewing environment, either grass or rocks are referenced.	MP
	34:50	City	Bright	Fog	"There are cars, or something, or bicyclists"	VH
	38:59	City	Dark	Clear	"There is something zooming around here, could be a car or bicyclist."	VH
	39:45	City	Dark	Clear	Previously identified target tree is not clearly labeled. "Tree or bush?"	MP
	41:45	SciFi	Dark	Fog	Identifies a sled while looking at the chairs after identifying a precipitation effect as snow.	MP
	43:37	City	Dark	Fog	A circle on the ground with an x is labeled as a sewer cap.	MP
11						
	30:28	Forest	Dark	Clear	Previously identified target person is now new. "There is a new guy, looks mean. Kind of a warrior looking dude."	MP
	32:20	City	Dark	Clear	Distant support pillars are labeled as "planters with little plants"	MP
VH-						
2						
	10:02	Forest	Dark	Clear	A mushroom that stopped being rendered due to object culling was labeled as "a butterfly just flew away"	MP
	13:15	Room	Dark	Fog	A lamp was labeled a book.	MP
8						
	23:13	SciFi	Light	Fog	Furniture appears bigger during this trial.	MP
	30:54	SciFi	Dark	Fog	"Chicken and a fish" points at the fish target then looks around for the chicken but can't find it	VH
9						
	13:49	Forest	Dark	Fog	Looks at background and reports seeing chairs. When prompted to return to review chairs are gone.	VH
	14:32	Forest	Dark	Fog	"I think that is the chicken" when looking in the vicinity of the fish target and a background rock	MP

Table 3. Summary of abnormal perceptive events in virtual reality. Conditions under which the event occurred, description of the phenomena as produced by reviewing the screen recording and participant verbal description, and the clinical label of the event. MP – misperception, VH- visual hallucination.

Participant ID	Misperceptions	Visual Hallucinations
VH+		
1	4	0
4	2	1
6	0	0
7	1	1
10	4	2
11	2	0
Mean	2.17	0.67
VH-		
2	2	0
3	0	0
8	1	1
9	1	1
12	0	0
Mean	0.80	0.40

Table 4. Summary of perceptual error events by participant and participant type.

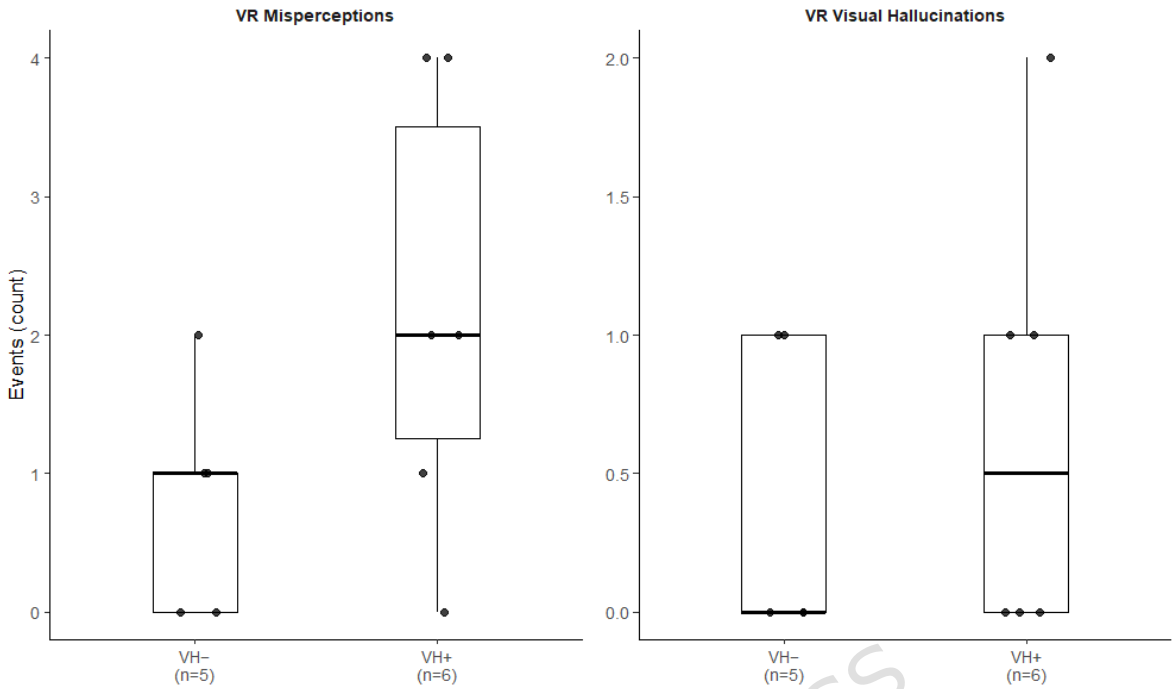

Figure 2. Boxplots of VR events for MP and VH for historically defined VH+ and VH- groups. Points added for each participant with jitter set at width = 0.1 and height = 0.

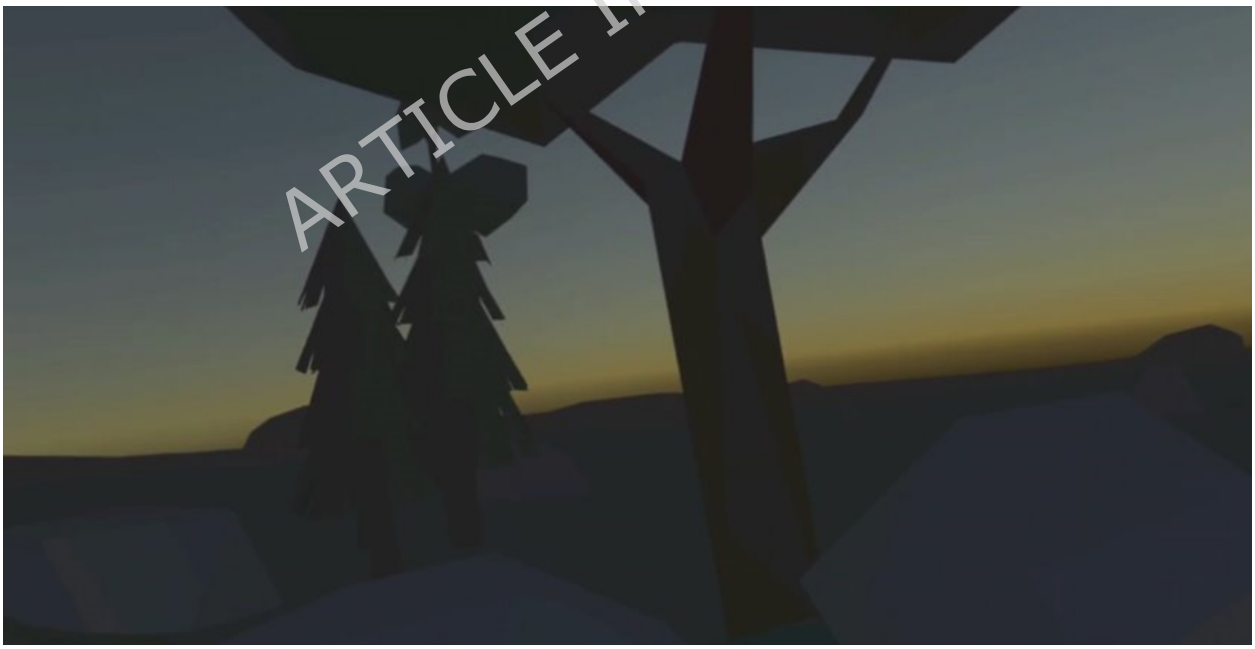

Figure 3. Screenshot from the virtual environment during the event described by participant 1.

Adverse events and tolerability

No severe adverse effects were noted and only participant 1 experienced a moderate adverse effect (dizziness). Otherwise, participants experienced no effects or reported mild dizziness, eye strain, physical discomfort, and/or emotional distress. All participants reported that they were willing to return for future testing and most (6/11) were willing to take the device home. During the debrief, several participants were interested in adding complexity, adding features they felt would better induce abnormal perceptive function, and gamifying the experience. Finally, more generally participants were willing to use a VR device as part of their treatment or clinical care in clinic (9/11) and at home (8/11).

Discussion

This pilot study supports the feasibility of utilizing structured virtual reality environments to evaluate visual perceptual dysfunction in individuals with Lewy Body Disorders. Critically, we show that it is technically possible to elicit and systematically characterize perceptual errors in VR. However, given the small sample size and methodological limitations our findings should be interpreted as preliminary and hypothesis-generating rather than confirmatory.

Most fundamentally, this study demonstrates that VR-based assessment of perceptual function can be done safely without notable immediate adverse events, even in sensitive populations with cognitive and psychiatric disturbances. While VR has been shown to be well tolerated with LBD in the context of motor rehabilitation [28], there were reasonable concerns about the safety of evaluating neuropsychiatric symptoms with this technology. These concerns were not observed in this pilot. In fact, participant interest and feedback in this study speaks to the possibility of producing assessment tools that are both clinically useful, but also enjoyable for users and which can function to provide data, multimodal therapy, and entertainment.

The findings of this study also suggest that this methodology is capable of capturing features related to visual hallucinations. VR-based perceptual error events behaved similarly to clinical VH as both became more frequent in low light environments where visual stimuli were ambiguous and tended to occur in certain settings [26]. Such visually degraded environments have historically been associated with hallucination emergence, and the interaction between sensory degradation and impaired visual processing has been postulated to play a role in perceptual misinterpretation and visual hallucinations [29]. Notably, perceptual error events were observed more frequently in VR than would be inferred from retrospective interview alone and had phenomenology that aligned with those reported historically in clinical interviews, though they critically did not fully replicate them. Additionally, while there was a trend to more abnormal perceptive events in VR in the VH+ group when compared to the VH- group, this was not statistically significant. The absence of a statistically significant group difference represents a critical limitation and may reflect limited statistical power as well as methodological constraints inherent to this prototype implementation. Accordingly, we are not able to conclude from this study that this methodology discriminates between those with and without VH or that it recreates real-world hallucinations, but this methodology does provide

a structured framework through which perceptual vulnerabilities may be probed.

Importantly, the current VR implementation had notable technical limitations that must be considered when interpreting results. As visible in the supplementary material, certain environments contained visual inconsistencies, including unintended stimulus fluctuations and rendering instability. These artifacts were not systematically controlled and may have influenced perceptual experiences in some instances. In addition, visual environments were presented in a fixed sequence, introducing the possibility of order, learning, or fatigue effects. Medication timing and ON/OFF dopaminergic state were not systematically manipulated or standardized and may also have influenced results. Future iterations of this methodology should prioritize environmental stability, assess the impact of artifacts, evaluate sequencing effects, and control for dopaminergic medication state. Accordingly, the present study should therefore be considered a prototype platform demonstrating feasibility rather than a finalized clinical instrument.

Methodologically our approach to assessing perceptual dysfunction is imperfect. Reliance on verbal descriptions allows confounding due to speech and language production errors (i.e. accidentally saying the wrong word or not saying anything because of forgetting the word). We believe these errors to have been rare as during our calibration task participants labeled target objects consistently and correctly. However, we did see that some individuals, especially in the VH+ group, struggled to articulate their perceptions and had reduced verbal output. We explored this utilizing speech recognition technology and found lower word counts for VH+ participants suggesting that language deficits were reducing the performance of our perceptual measures (unpublished). Future studies should explicitly and vigorously assess speech and language dysfunction, as well as other cognitive and visual deficits, and adjust perceptual measures based on these features.

There remains substantial work to develop clinically utilizable digital biomarkers for visual hallucinations and perceptual dysfunction. Larger and more demographically diverse cohorts of participants will be required. Critically, there should be a focus on incorporating individuals with both visual misperceptions and hallucinations, and there should be exhaustive phenotyping of the phenomena to understand associated affect and insight. Further these studies should evaluate the reliability of generated measures and the sensitivity of measures to established treatment effects, including

antipsychotics and dopaminergic excess. This performance should again be compared to standard and novel clinical and neuropsychiatric measures such as pareidolia testing using the NPT-20 and numerosity estimation. The specificity of this methodology will need to be assessed in healthy controls, individuals with ophthalmologic disease, and other neurodegenerative disorders.

Finally, translation into a practical, reliable, and meaningful clinical tool will require automation of perceptual event detection and classification. We propose that this could be accomplished by use of eye tracking data for the identification of visual stimuli (or lack of stimuli) combined with speech-recognition based user narratives to produce perceptual event metrics. We took the first step in this direction by utilizing eye tracking to assist with event review by clinicians, but future efforts should focus on utilizing visual fixation events and patterns to automate this methodology; however, substantial validation work is necessary before automation can be implemented reliably.

In summary, this pilot study demonstrates the technical and clinical feasibility of VR-based methodologies for the assessment of visual hallucinations and abnormal visual perceptual function in Lewy body disorders. While limited by small sample size and technical constraints, the findings support continued development of structured VR tools for studying perceptual dysfunction and represent an early step toward the potential development of clinically implementable monitoring systems that comprehensive evaluate the manifestations of neurodegenerative disorders.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request. The code produced in house is available at https://doi.org/10.5281/zenodo.18670154.

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