Immersive Virtual Reality Alters Behavioral and Neural Markers of Spatial Attention

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Abstract

Traditionally, cognitive neuroscience experimentation has relied on tightly controlled laboratory settings that often lack ecological validity. This study examined whether immersive stereoscopic virtual reality (VR) alters attentional orienting and its neural correlates by embedding a classic Posner cueing task within a three-dimensional environment while recording electroencephalography (EEG). Thirty-five participants completed 2D and VR versions of the task. Behaviorally, the classic cueing effect was observed in both conditions: faster reaction time and higher accuracy for valid trials. However, despite overall slower reaction times in VR, attentional reorienting costs were significantly reduced. Event-related potential analyses revealed no early validity effects on P1 or N1 components, potentially reflecting inhibition of return or increased visual complexity. The P3 component showed larger amplitudes for invalid trials and a posterior topographical shift in VR. These findings suggest that immersive stereoscopic contexts preserve core attentional effects while biasing processing toward more perceptually grounded, bottom-up mechanisms.

Keywords: cognitive neuroscience; attention; virtual reality; Posner; stereovision

Introduction

The aim of cognitive science has generally been to explain how the mind operates in real-life situations, yet much of what is known about perception and attention derives from experiments conducted under highly simplified laboratory conditions that fail to reflect the real world. Participants are typically seated in front of flat, two-dimensional (2D) displays and respond to simplified stimuli (Danziger, 1994; Hatfield, 2002; Holleman et al., 2020; Kingstone et al., 2008). While this laboratory-based approach has been a fundamental building block for the scientific understanding of perception (Gong et al., 2022), it has also prompted longstanding concerns regarding ecological validity (Jenkins, 1974; Neisser, 1976; Shamay-Tsoory & Mendelsohn, 2019).

Ecological validity is particularly relevant for theories of attention, which aim to characterize how cognitive resources are allocated in dynamic environments. Classic paradigms, such as the Posner cueing task, have played a foundational role in shaping contemporary models of spatial attention (Posner, 1980, 2016). The Posner task focuses on mechanisms of attention and spatial cueing, and laid the groundwork for subsequent research in cognitive psychology and neuroscience (e.g., Driver et al., 1998; Feher Da Silva & Baldo, 2015; Nasiri et al., 2023; Posner, 2022; Ristic & Kingstone, 2009). The findings from research using the Posner task have created the basis for a major theoretical framework regarding attentional processes (Corbetta & Shulman, 2002; Posner, 1978; Rafal et al., 1989), establishing a widely accepted distinction between exogenous (reflexive) and endogenous (voluntary) attentional control mechanisms (e.g., Berger et al., 2005; Jonides, 1981).

Despite their theoretical importance, these conclusions have been drawn almost exclusively from 2D paradigms. Real-world perception is inherently three-dimensional, integrating binocular disparity, motion parallax, and embodied perspective into a structured scene representation (Brenner & Smeets, 2018; Cumming & DeAngelis, 2001; Wheatstone, 1838). Stereoscopic depth contributes to spatial localization in near space and supports the figure–ground segmentation by which objects become individuated attentional units. Because 2D paradigms eliminate these cues, it remains unclear whether attentional dynamics observed in such tasks reflect general mechanisms or are partly shaped by the impoverished depth structure of flat displays.

Virtual reality (VR) provides a promising means of addressing this gap by allowing researchers to embed cognitive tasks within immersive, stereoscopic environments while maintaining experimental control over stimulus timing and spatial structure (De Gelder et al., 2018; Peeters, 2019). VR allows for key features relevant to ecological validity, including realistic environments and stimuli (Newman et al., 2022), stereoscopic depth (Scarfe & Glennerster, 2019), and expanded field of view (Scarfe & Glennerster, 2019). Previous work suggests that VR can modulate behavior and neural activity across a range of cognitive domains, often engaging perceptual and attentional processes more strongly than traditional displays (Aksoy et al., 2021; Harjunen et al., 2017; Slobounov et al., 2015). Nevertheless, relatively few studies have directly compared identical cognitive tasks across 2D and immersive stereoscopic conditions (e.g., Burns & Fairclough, 2015; Slobounov et al., 2015). Burns and Fairclough (2015) compared gameplay on a standard 2D display and in VR using auditory event-related potentials as an implicit index of attentional engagement and found that task demand, rather than display modality, primarily drove neural markers of attention. In contrast, Aksoy et al. (2021) reported comparable P3 responses across 2D and VR during an n-back task, alongside enhanced early visual components (P1/N1) in VR, suggesting that immersive presentation may selectively modulate early sensory processing without uniformly altering later cognitive

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stages. Accordingly, the extent to which attentional mechanisms characterized in traditional two-dimensional paradigms generalize to immersive VR environments remains unclear.

The present study addresses this question by embedding a classic Posner cueing task within an immersive VR environment and directly comparing behavioral and neural indices of attentional orienting with a visually matched 2D version of the task. Electroencephalography (EEG) was used to assess whether immersive stereoscopic contexts alter the temporal dynamics or cortical distribution of attention-related neural activity, focusing on established event-related potential (ERP) components associated with attentional orienting and target evaluation (Gómez & Flores, 2011; Hopfinger et al., 2000; Polich, 2007). By using a well-established paradigm, this approach enables a targeted test of whether attentional mechanisms inferred from traditional 2D studies generalize to more ecologically grounded perceptual conditions.

Briefly, the Posner spatial cueing task examines covert attentional orienting by measuring responses to targets preceded by congruent (valid) or incongruent (invalid) cues that indicate target location (Posner, 1980). Cues are centrally (e.g., symbolic arrows at fixation) or peripherally presented (e.g., abrupt onsets near a potential target location), and engage what is thought to be either endogenous or exogenous orienting mechanisms, respectively (Jonides & Irwin, 1981). Typically, the cueing stimuli are statistically associated with the target's location, usually with around 80% chance of a valid trial and 20% chance of invalid (Johnson et al., 2023; Martinez-Alvarez et al., 2021; McCann et al., 1992; Posner, 1980). The predictive nature of the cues creates an expectancy effect, where participants start to rely on the cue to predict the target's location (Posner, 1980, 2016). Thus, researchers can measure how participants allocate their attention based on these expectations (Posner, 1980, 2016; Ristic & Kingstone, 2009).

Robust findings demonstrate that valid cues reliably produce faster and more accurate responses than invalid cues, which are thought to incur costs associated with disengaging and reorienting attention (Posner, 1980, 2016). Electrophysiologically, spatial attention in the Posner task modulates early visual processing of targets, with validly cued targets eliciting enhanced P1 and N1 amplitudes over contralateral occipital scalp sites, reflecting facilitated sensory processing at attended locations (Luck & Hillyard, 1994; Mangun & Hillyard, 1991). Invalid targets usually evoke a larger P3 component, which has been linked to attentional reorienting and context updating demands (Polich, 2007).

The present study tests two competing predictions about how immersive VR alters spatial attention. A *top-down enhancement* account predicts that the spatial realism and embodied context of VR should strengthen endogenous attentional engagement, producing larger cueing effects behaviorally and amplified P1/N1 and P3 components neurally (Aksoy et al., 2021; Slobounov et al., 2015). A *bottom-up reweighting* account predicts the opposite: stereoscopic depth should enhance the perceptual salience of targets, increasing exogenous attentional capture and thereby *reducing* the cost of reorienting on invalid trials, with neural processing shifting toward more posterior, sensory-driven mechanisms. We additionally test whether classic contralateral P1/N1 modulations are preserved in immersive contexts, given prior evidence that these early markers are sensitive to cue–target timing and display complexity (Martín-Arévalo et al., 2016).

Method

Participants

Sample size was determined via a simulation-based power analysis with effect sizes estimated from pilot data ($N = 24$). With a target sample of 30 participants, simulated power to detect a main effect of display condition on reaction time was 88%; power for accuracy effects was substantially lower, reflecting the small effect observed in pilot data. Thirty-six participants (22 females, 12 males, 2 other; mean age = 19.12 years; 34 right-handed, 2 left-handed) were recruited for the study. One participant was excluded from analysis due to only completing the 2D portion of the experiment. Thus, 35 participants were included in the final analysis. All participants reported having normal or corrected-to-normal vision, no history of visual disorders, and $\leq$10 hours of prior VR experience. Course credit was given for participating in the study. Prior to participation, written informed consent was obtained from all participants. Participants were randomly assigned to complete either the VR or 2D condition first, with the order counterbalanced across the sample.

Stimuli and Apparatus

A modified Posner task was programmed in Unity in both 2D and VR (Unity Technologies, 2024). The 2D and VR versions were visually identical, except the VR version included stereoscopic depth. The VR condition was presented binocularly via an HTC VIVE XR Elite head-mounted display (HTC Corporation, New Taipei City, Taiwan) at a per-eye resolution of 1920×1920 pixels (3840×1920 combined), a 90 Hz refresh rate, and an approximately 110° diagonal field of view. Inter-pupillary distance was adjusted individually for each participant prior to the start of the VR block. Unlike a typical Posner task, in which stimuli appear on a white or gray background, the current task placed objects in a 3D room with a floor, ceiling, walls, two couches, and a ceiling light. The semi-realistic background was created in order to decrease discomfort for participants, as solid color backgrounds were found to be too uncomfortable during pilot testing, and increase the risk of cybersickness. In the 2D condition, participants viewed the display from approximately 81 cm (nose-to-screen). The target orb subtended approximately 5.4° of visual angle and appeared at 11.5° eccentricity from the central fixation; the arrow cue subtended approximately 1.8° of visual angle. In the VR condition, stimulus dimensions were calculated within Unity such that the target orb and arrow cue subtended the same visual angles and eccentricities as in the 2D condition.

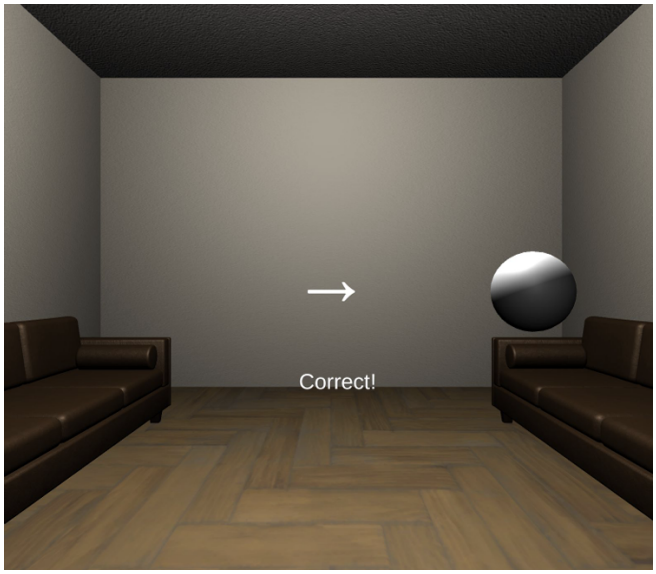

Figure 1: Experimental stimuli and environment. The Posner task was placed in a semi-realistic room with two couches. The cueing stimulus was an arrow pointing to the left or right, and the target was a gray orb appearing on the left or right. Feedback was shown below the task.

During each trial, participants fixated on a central cross in a virtual room (or on the 2D screen), which was replaced by a left- or right-pointing arrow cue. A gray orb target then appeared on either side of the display. A trial was valid when the cue pointed towards the location of the target, and an invalid trial when it pointed to the opposite direction. Participants responded by pressing the trigger on the corresponding (left or right) HTC VIVE controller; the same controllers were used in both 2D and VR conditions, equating the response device across environments. Feedback ("Correct" or "Incorrect") was provided after each response. Cue, target, and inter-trial intervals were randomly sampled from a uniform distribution between 0.5 and 1.0 seconds. Responses not made within 1 s were recorded as no responses, and incorrect button presses were logged separately. Trial type, cue direction, and target location were randomized, with 80% valid and 20% invalid trials. Figure 1 illustrates the visual layout of the task environment and stimuli.

Procedure

At the beginning of each condition, participants completed a brief practice session consisting of 20 randomized trials to familiarize themselves with the task. The main experiment was split into two conditions (VR and 2D), with each condition having two blocks of 200 trials, totaling 400 trials per condition and 800 trials across the full experiment. Thus, each participant underwent 640 valid trials (80%) and 160 invalid trials (20%). Each condition took about 20 minutes to complete. Participants received verbal and written instructions to focus on the fixation cross throughout the task, and press the right button for targets appearing on the right and left for targets appearing on the left. They were instructed to respond as quickly and accurately as possible and were provided short breaks between blocks to minimize fatigue. After completing the first condition, participants were given an extended break while the setup was reconfigured for the alternate 2D or VR condition.

EEG Recording and Processing

EEG data were continuously recorded during the behavioral task using the BrainVision acquisition system with *BrainVision Recorder* software and 63 active Ag/AgCl electrodes embedded in an elastic fabric cap (ActiCap Snap; Brain Products GmbH, Gilching, Germany). The ActiChamp Plus system amplified and digitized the signals at a sampling rate of 1,000 Hz. Electrode impedances were kept below 10 kΩ. The ActiChamp system employs a Global Field Power reference, whereby the average of all electrodes serves as both ground and reference (Brain Products GmbH, 2023). During VR blocks, thin foam padding was placed between the head-mounted display and the EEG cap at points of contact to prevent pressure on the electrodes. No additional channels were excluded as a result of headset interference. Event triggers were sent to the EEG recording to mark cue onset, target onset, and button press events.

EEG data were processed offline using *BrainVision Analyzer 2.3.0* (Brain Products GmbH, 2022). Signals were filtered with a 0.1 Hz high-pass and 40 Hz low-pass zero-phase Butterworth filter and re-referenced to the common average. Data were epoched from −200 to 800 ms relative to target onset and baseline-corrected using the prestimulus interval. Artifacts were automatically rejected using standard amplitude and gradient criteria, including ocular channels, and contaminated epochs were excluded. Remaining epochs were averaged by condition to obtain ERP waveforms.

ERP amplitudes were quantified using area-under-the-curve (AUC) measures within predefined latency windows for the (1) P1 component (90–190 ms, measured over electrodes P5, P6, P7, P8, PO3, PO4, PO7, PO8); (2) N1 component (170–250 ms, measured over the same electrodes as the P1 component); (3) P3 component (300–600 ms, measured over electrodes Fz, FCz, Cz, CPz, Pz, POz). Contra–ipsilateral difference scores were computed where applicable and analyzed using mixed-effects models testing Display (2D vs. VR) and Validity (valid vs. invalid). Peak amplitudes were additionally analyzed using mixed and ordinary least squares models with cluster-robust standard errors. To assess potential differences in the scalp distribution of the P3 component across display environments, normalized P3 AUC amplitudes were additionally analyzed as a function of anterior–posterior electrode position using linear mixed-effects models.

Results

Behavioral

Reaction times (RTs) were analyzed using a linear mixed-effects model with fixed effects of Condition (2D vs. VR), the contrast-coded factor Validity, their interaction (Condition × Validity), Order (2D-first vs. VR-first), and Trial Index (the sequential position of each trial within a block), with random intercepts and random slopes for Validity by participant (N = 35). RTs were log-transformed to correct skew and trimmed to remove outliers (< 100 ms or > 1500 ms, plus ±2.5 SD within each participant × condition × trial-type cell).

The model revealed a significant main effect of Condition (β = 0.138, SE = 0.004, z = 32.84, p < .001), indicating that participants were slower in VR than in 2D (approximately 14.8% longer RTs, equivalent to about 45 ms slower in VR than in 2D). A strong main effect of Validity was also observed (β = 0.159, SE = 0.015, z = 10.86, p < .001), reflecting the expected attentional reorienting cost, in which invalid cues produced slower responses than valid cues. The Condition × Validity interaction was significant (β = –0.025, SE = 0.009, z = –2.86, p = .004), indicating that the attentional reorienting cost was smaller in VR than in 2D.

Accuracy was analyzed at the trial level using a binomial GEE with the same fixed-effect structure and participant as the clustering factor (N = 35). Overall accuracy was high (M = .97). The model revealed a significant main effect of Validity (β = –1.50, SE = 0.21, z = –7.08, p < .001), confirming that participants were less accurate on invalid (M = .91) than on valid (M = .98) trials. The main effects of Condition (β = 0.16, SE = 0.23, z = 0.71, p = .48) and Order (β = 0.38, SE = 0.24, z = 1.59, p = .11) were nonsignificant, as was the Condition × Validity interaction (β = –0.07, SE = 0.20, z = –0.34, p = .74), indicating that the effect of validity on accuracy did not differ significantly between environments.

Trial sequence effects were also examined. The effect of Trial Index was small but significant (β < 0.001, SE < 0.001, z = 8.08, p < .001), indicating a gradual increase in RTs over the course of the task (≈5 ms per 100 trials). No corresponding effect of Trial Index was observed in the accuracy model (β = 0.0004, SE < 0.001, z = –1.10, p = .27).

EEG

ERP amplitudes were quantified using AUC measures within predefined latency windows (see Methods). Statistical analyses focused on effects of Display (2D vs. VR), Validity (valid vs. invalid), and, where applicable, hemispheric laterality or anterior–posterior scalp position.

P1 AUC amplitudes showed no significant main effects of Display or Validity, nor any interaction between these factors (all p > .30). Early sensory responses were therefore comparable across 2D and VR environments and were not modulated by attentional cue validity.

N1 AUC amplitudes exhibited a robust contralateral–ipsilateral difference, with larger (more negative) responses at electrodes contralateral to the target location (F(1, 34) = 16.2, p < .001). This lateralization effect did not interact with Display or Validity (all p > .25), indicating preserved spatially selective attentional processing across both display formats.

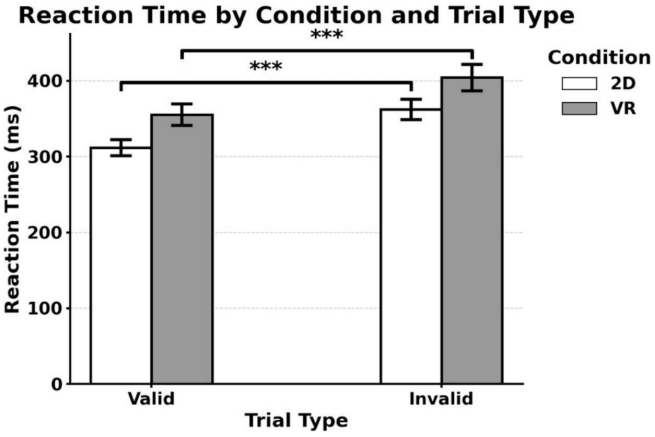

Figure 2: Reaction time by condition and trial type. Mean RTs (ms) for valid and invalid trials in the 2D and VR conditions. Error bars represent ±1 standard error of the mean. Participants responded significantly more slowly on invalid than valid trials (β = 0.159, SE = 0.015, z = 10.86, p < .001).

P3 amplitudes were larger for invalid than valid trials (F(1, 34) = 6.5, p = .011), consistent with classic attentional reorienting effects. Overall P3 magnitude did not differ between display environments, and no Display × Validity interaction was observed (both p > .35). In contrast, the scalp distribution of the P3b component differed across environments, with a more posterior expression in VR relative to 2D (Display × anterior–posterior position: β = 0.020, SE = 0.008, z = 2.50, p = .012). A main effect of anterior–posterior position was also observed (β = –0.034, p < .001), reflecting the canonical posterior distribution of the P3b.

Discussion

The present study examined how immersive stereoscopic VR influences attentional orienting and its neural correlates relative to a traditional 2D display. Overall, the findings indicate that while classic attentional effects are preserved in VR, behavioral efficiency and the neural distribution of attentional processing are altered, with implications for ecological validity in cognitive neuroscience.

Behaviorally, the classic Posner cueing effect was robustly replicated in both 2D and VR: participants responded more quickly and accurately in valid trials. Thus, the core attentional mechanisms engaged by the task remained intact across display formats. Overall RTs were slower in VR, consistent with prior work suggesting that immersive environments impose greater perceptual and cognitive load (Makransky et al., 2019; Schrader & Bastiaens, 2012). Critically, the attentional reorienting cost, operationalized as the RT difference between invalid and valid trials, was significantly smaller in VR than in 2D, indicating a reduced penalty for reorienting attention

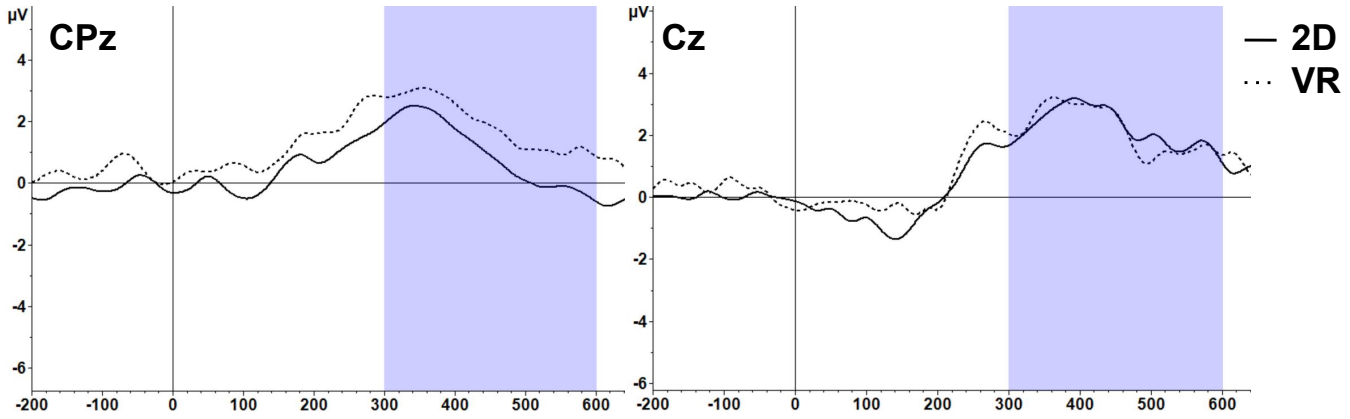

Figure 3: Invalidly-Cued Targets in 2D and VR. Grand-averaged ERPs time-locked to invalid-target onset for 2D and VR conditions. Left: At CPz, the P3 amplitude is visibly larger for VR than for 2D. Right: At Cz, the P3 component is no longer significantly different between 2D and VR. These ERP waveforms illustrate that display-related differences in P3 amplitude may vary by scalp location. Shaded regions denote the 300–600 ms analysis window; negative is plotted downward.

following invalid cues, or a more efficient reallocation of attention.

ERP analysis found larger P3 amplitudes for invalid than valid trials, consistent with classic accounts linking the P3 to attentional reorienting and increased evaluative demands when expectations are violated. Overall P3 amplitude did not differ between the 2D and VR conditions, nor was there a Display × Validity interaction, indicating that immersive presentation did not globally amplify neural responses associated with reorienting. Instead, VR selectively altered the scalp distribution of the P3 component, which exhibited a more posterior expression relative to 2D. This posterior shift suggests that attentional evaluation in VR relied more heavily on perceptual processing regions, consistent with increased stimulus salience and greater engagement of sensory-level representations during target processing.

Overall, these findings suggest that attentional orienting in immersive VR places relatively greater emphasis on stimulus-driven, bottom-up processing. Behaviorally, the reduced RT cost for invalid trials indicates faster reallocation of attention when targets appeared at unexpected locations in VR. One plausible explanation is that stereoscopic depth enhanced the perceptual salience of the target orbs in VR, supporting figure–ground segmentation and increasing exogenous attentional capture by the target itself. Under this account, even on invalid trials attention may be rapidly drawn to the uncued side by the target's salience, thereby shortening reorienting time and reducing the invalid–valid RT difference. Converging with this behavioral pattern, the more posterior expression of the P3 component in VR suggests that attentional evaluation relied more heavily on perceptual processing regions when targets appeared. Rather than reflecting a global amplification of attentional resources, this redistribution implies a reweighting of attentional processing toward sensory-level representations in immersive stereoscopic contexts.

Although early visual components (P1 and N1) were elicited, these components did not show the typical validity modulation observed in prior studies (Gómez & Flores, 2011; Hopfinger et al., 2000; Mangun & Hillyard, 1991). This absence may reflect inhibition of return, given that cue–target intervals overlapped with temporal windows in which facilitation at cued locations can be suppressed (Klein, 2000; Posner, Cohen, et al., 1984). Prior work indicates that P1 modulation is highly sensitive to cue–target interval and task context, and that after long cue–target intervals (>500 ms) P1 effects are often reduced or absent even when behavioral facilitation persists, suggesting that early sensory gain is not a necessary correlate of endogenous spatial cueing (Martín-Arévalo et al., 2016). Furthermore, N1 modulations have been reported to be inconsistent and strongly dependent on task demands and temporal parameters. In particular, studies employing long cue–target intervals or complex visual displays frequently report behavioral cueing effects in the absence of N1 modulation (Martín-Arévalo et al., 2016).

Several limitations warrant consideration. While visual angles were equated by calculation, stimulus salience itself was not independently measured; observed effects may partly reflect enhanced perceptual salience of stereoscopically rendered targets, consistent with the bottom-up reweighting account proposed above. Slower RTs in VR suggest that immersion introduces perceptual and cognitive costs, potentially due to increased sensory complexity, stereoscopic processing demands, or headset novelty. Additionally, the virtual environment, while immersive, remained visually simplified relative to real-world settings. Future work should examine how dynamic interaction, multisensory cues, and more complex environments further shape attentional processing in VR.

In summary, immersive VR preserves classic attentional effects while altering both behavioral performance and the neural distribution of attentional processing. By leveraging stereoscopic depth cues, VR provides a promising platform for studying attention under controlled conditions that better

approximate real-world perception, offering new insights on theories of attentional control and ecological validity.

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