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Adaptive Depth Calibration Training Reduces Spatial Anxiety and Enhances Spatial Task Performance

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Abstract

Objectives: The primary aim of this study is to assess and investigate anxiety in simulated environments, and to measure changes in spatial anxiety, maze navigation time, and depth judgment accuracy in pre-, post-, and retention conditions. **Methods:** This study implemented a quantitative experimental approach using a within-subject design to investigate the effects of adaptive depth calibration training on spatial performance and anxiety. Participants completed a series of spatial cognitive tasks across all three conditions, such as measuring anxiety scores, navigation time, and depth judgment accuracy. This quantitative design enabled an exact comparison of individual progress over time and provided objective evidence of the intervention's effectiveness, without relying on qualitative feedback. **Findings:** There is a statistically significant increase in scores in the post-adaptive depth calibration training compared to pre-training. The results indicated that spatial anxiety decreased from 50.0 (11.2) to 40.1 (8.5) immediately after the training and remained at 43.1 (9.1) in the retention period. Secondly, the average maze completion time improved from 65.4 (13.0) seconds to 47.5 (10.5) seconds, and remained at 51.0 (11.5) seconds after two weeks. Depth judgment accuracy was increased from 62.5% (9.0%) to 78.6% (8.0%) with a mean of 76.7% (8.5%) at retention. This suggests that the adaptive training had a specific impact, increasing spatial ability and confidence in the participants. **Novelty:** Unlike prior studies on VR training that typically reported on speed improvements alone, this study jointly improved accuracy (+26.9%), navigation time (-25.6%), and spatial anxiety (-21% immediate; -13% at retention) on non-adaptive, gold-standard tests, emphasising a multi-metric, durable benefit that recent studies rarely show together.

Keywords: Spatial Training; Depth Perception; Spatial Cognitive Anxiety; Cognitive Performance Enhancement

1 Introduction

Spatial perception focuses on navigation, engineering design, and data-driven decision-making. However, the evidence suggests that the most effective way to train these skills remains unclear across various platforms, measures, and learner profiles. A systematic literature review and framework study on adaptive virtual reality (VR) training argues that personalisation can improve learning but also notes heterogeneity in tasks, short follow-ups, and limited triangulation of behavioural and affective outcomes, making it difficult to compare effects across studies[(1)]. Personalised, game-based models validate that adaptive difficulty can increase high-level performance; however, these studies are often domain-specific (e.g., first-person shooters), emphasise speed or score rather than perceptual reliability, and rarely report retention beyond the immediate post-test[(2)]. In depth-related work, proof-of-concept VR procedures that scaffold binocular cues have shown early improvements in stereovision, but with small samples and pilot designs that compel applicability and statistical control[(3)]; related perceptual-learning studies in older adults confirm plasticity later in life yet leave open whether benefits decode to broader adult populations and to multi-component spatial tasks (navigation plus depth judgment)[(4)]. Even when stereoscopic video game introductions improve depth precision, accuracy itself does not always improve, highlighting a precision-accuracy tension that training protocols must explicitly address if they aim to develop real-world spatial judgments rather than relying solely on lab metrics[(5)]. Parallel to this, the affective ground of spatial work remains under-integrated. VR studies show that spatial anxiety can be induced and modulated in navigation contexts, but most training trials do not embed anxiety reduction as a co-primary endpoint or track its durability after initial improvements[(6)]. Converging evidence shows that spatial anxiety both covaries with and mediates sex differences on core spatial tasks, suggesting that any effective intervention should measure and target anxiety to close performance gaps rather than treat it as a by-product[(7)]; motivational factors likewise shape outcomes under time pressure and uncertainty, reinforcing the case for designs that adapt difficulty to maintain engagement without overload[(8)]. Meta-analytic work further shows that gender-related disparities in spatial cognition persist into adulthood, which strengthens the need for interventions capable of reducing gaps in typical learner groups rather than in narrowly defined subgroups[(9)]. Finally, spatial learning depends on the amount of information that must be integrated from the environment. When integration difficulties are high, working-memory limits constrain increases, making real-time calibration of task difficulty, not just fixed levels, an essential element for effective training[(10)].

On the other hand, the present study addresses four persistent gaps: (i) it integrates three outcome relations, spatial anxiety (because environmental cognitive load increases spatial anxiety during navigation[(11)]), navigation efficiency, and depth-judgment accuracy[(12)] within a single procedure to provide a multi-dimensional view of change (where much prior work isolates one outcome)[(5)]; (ii) it implements continuous, trial-by-trial adaptive depth calibration to tackle the precision-accuracy skill directly rather than rely on rough level jumps[(6)]; (iii) it embeds affect as a planned endpoint and evaluates durability with a retention test, moving beyond immediate post-training phases that dominate the literature[(8)]; and (iv) it tests whether an adaptive simulation can reduce gender disparities that remain evident in recent combinations, thus converting description of gaps into a targeted equity outcome[(7)]. Therefore, we designed a closed-loop depth calibration that explicitly targets the precision–accuracy[(5)] gap while treating anxiety reduction as a co-primary objective, and we separated adaptive practice from fixed, non-adaptive tests with a retention check[(1)]. This combination of triangulating accuracy, speed, and affect in one study highlights the most consistent gaps in recent work and provides a practical template for STEM-relevant training in typical adult learners.

2 Methodology

2.1 Research Design [Figure 1]

We administered a within-subject, repeated-measures experiment with three assessment points: pre-test (baseline), immediate post-test, and 2-week retention. All tasks were carried out in a desktop simulation that recorded trial-level responses, timestamps, and adaptive difficulty states. The sequence at each visit was: Spatial Anxiety Scale[(13)] $\rightarrow$ virtual maze navigation (time to completion, s)[(14)] $\rightarrow$ depth-judgment task (percent correct)[(15)], followed by 45-60 minutes of adaptive depth-calibration training and then the post-test phase; the retention visit reproduced the post-test using parallel forms to limit test-retest familiarity. Depth-delta values were adjusted in separate steps (5-10% of the current level) based on trial-wise performance, with upper and lower limits set to avoid floor and ceiling effects. This hybrid of personalised (adaptive) training with fixed, non-adaptive evaluation blocks aligns with current recommendations for VR/adaptive training research and generalisation testing[(1)]. To support affect-performance integration, anxiety was treated as a co-primary endpoint given recent evidence that spatial anxiety is both flexible in VR contexts and functionally related to spatial task performance[(7)].

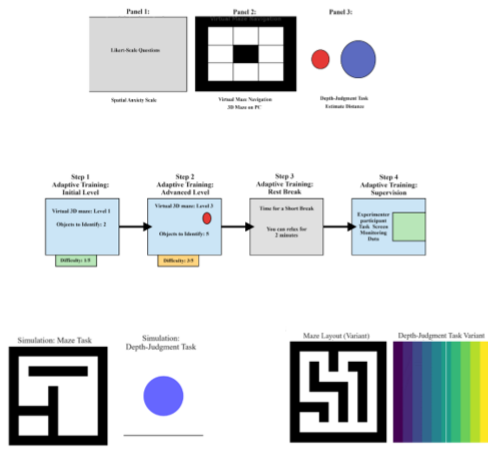

Fig 1. Research Design Overview: Phases (pre-test, post-test, retention); task sequence (Spatial Anxiety Scale, maze navigation, depth-judgment); and adaptive training flow with parallel forms for retention.

2.1.1. Participants

Seventy-five participants (37 men, 38 women; 18-25 years) with normal or corrected to normal vision and no specialized 3D training background were recruited for this study. Informed consent and each served as their own control across sessions.

2.1.2. Data Collection

We collected data through behavioural trial logs, i.e. correct trials, response times, adaptive parameters, and task identifiers automatically via the simulator's logger. The second method was collected through questionnaire totals for spatial anxiety, using multifaceted measures [(13)].

2.1.3. Inputs & Outputs

At the input level (trials/sessions), phases (pre, post & retention), task (maze & depth), adaptive parameters (object counts, layout complexity, depth deltas, a choice made to keep information manageable. This is based on the connection between environmental load and spatial anxiety [(11)]), response time per trial, trial correctness and participant's sex. Outputs are (analytical level) 1. Spatial anxiety (total score, lower is better), 2. Maze completion time in seconds (lower is better) and 3. Depth judgement accuracy (as % correct), the higher the better. These outputs reflect the primary performance and support recent studies on stereovision/VR in adaptive training [(9)].

2.2 Research Gap

Recent adaptive/VR studies show potential, but typically focus on single outcomes [(12)], use short follow-ups, or fail to separate training from non-adaptive evaluation, which undermines transfer claims [(1)]. Depth-perception related work reveals a precision–accuracy tension, where precision can improve while accuracy remains unchanged, suggesting that studies must calibrate the informational content of depth cues, rather than merely increase speed [(5)]. At the same time, spatial anxiety is rarely treated as a secondary endpoint despite evidence that it shapes performance and can mediate gender differences [(16)]. Additionally, environmental cognitive load increases spatial anxiety during navigation. This highlights the need to manage layout complexity during training and testing [(11)]. The purpose of this study is to test whether closed-loop depth calibration yields multi-metric improvements and effect accuracy, speed, and affect. On non-adaptive tests, it shows retention and reduces baseline gaps in a typical adult group.

2.2.1. Unique Traits and Contributions

This study combines four elements that are rarely reported together in adaptive VR training. First, it uses a multi-metric endpoint set that includes accuracy, speed, and affect measured on fixed, non-adaptive tests. Second, it features a closed-loop calibration that directly targets the precision-accuracy issue by adjusting depth deltas and layout complexity from one trial to the next. Third, it includes a retention assessment using parallel forms to test durability and transfer. Lastly, it applies an equity lens to show that baseline gender gaps narrow after training. Together, these choices tackle the field's most common limitations and position the protocol for practical use in STEM learning contexts[1].

2.3 Methods of Research

All sessions were conducted in a quiet laboratory with controlled lighting; the tasks were run on similar desktop systems equipped with standard keyboard and mouse[17]. The simulator presented 3D maze layouts and stereoscopic depth stimuli[18]. The post-test and retention tests used parallel and non-adaptive forms that matched the structure of the baseline/post-test tasks to minimize learning by repetition[2]. Data processing followed in a pre-specific manner: (a) removing practice screens, (b) technical failures/timeouts, and (c) extreme RT outliers. Maze times were assessed for skew and log-transformed when non-normal; accuracy and questionnaire totals were inspected for range. Simultaneous forms of retention were used to reduce memory effects while preserving task difficulties[4]. In line with adaptive-training evaluations[3], the task context was defined by the split: 1. Training set (60% of total trials) of adaptive session, where difficulty is adjusted trial-by-trial (skill question with feedback). 2. The testing set (40% of total trials) of non-adaptive post-test and retention sequences was similar across all the participants.

The primary metrics were spatial anxiety, maze completion time, and depth judgment accuracy. We calculated phase-wise means, within-subject changes in scores (pre- to post- and pre- to retention), percentage changes for interpretability, and retention ratios. For inference, we used repeated measures statistics with 95% CIs and effect sizes suitable for repeated measures designs, i.e., Cohen's d, to determine the magnitude of change and practical relevance[10]. To demonstrate improvements beyond the adaptive environments, superiority was assessed only on the standard and non-adaptive tests (post-test and retention).

2.4 Data Availability

All trial-level logs from all phases, parallel stimulus variants, and analysis scripts will be available to the public at the GitHub data repository once accepted. The dataset contains anonymised raw task logs, processed summary scores, and analysis scripts used to generate the reported statistics and figures. https://github.com/sunderrathore-maker/Spatial-data. Accessed on 20/10/2025.

2.5 Ethics Approval

This study received IRB approval (UoH/2025-015). Written informed consent was obtained from all participants.

3 Results and Discussion

The following is the assessment of the adaptive depth calibration in three conditions: 1. Spatial anxiety, 2. Maze completion time, 3. Depth judgment accuracy.

3.1 Primary Results

The results indicate a consistent improvement across all tests. In spatial anxiety, the decrease was from 50.0 at baseline to 40.1 immediately after training (a reduction of 21.0%), and it remained lower at retention, 43.1 (with a significant decrease of 13.1% compared to initial baseline levels) (Table 1). Maze completion time improved substantially after training (by 25.6% faster). Maze time decreased from 65.4 s to 47.5 s and was 51.0 s at retention (−19.6% vs baseline at two weeks). Accuracy increased sharply from 62.5% at baseline to a peak of 74.1% post-training, signifying a 15.7-point (26.9%) improvement. Compared with recent adaptive VR studies[2] that often boost speed or scores without corresponding perceptual accuracy improvements, our results show a concurrent rise in accuracy[5] (+26.9%) and faster navigation (−25.6%) with retention, meeting the study objective of multi-metric improvement beyond the training context[16]. Improvements were observed on non-adaptive, standardised tests at post-test and retention, indicating generalisation beyond the adaptive environment[19]. These improvements were sustained for two weeks on fixed, non-adaptive assessments. Unlike stereoscopic play that improved precision without enhancing accuracy, the trial-by-trial adjustment of depth differences and layout complexity provided a genuine accuracy benefit that extended beyond the training context[12].

3.2 Spatial Anxiety Scale (SAS) scores

Females reported more anxiety than males at the start, with scores of 55.3 compared to 44.7; $t(72.99)=-4.59$, $p<0.001$, $d=-1.06$. Overall anxiety dropped from 50.0 ± 11.2 to 40.1 ± 8.5 and stayed at 43.1 ± 9.1 during retention. The difference in anxiety between genders after training was not significant and remained small at retention (Figure 2).

Table 1. Summary of pre-test, post-test, and retention outcomes (All participants; mean ± SD).

Measure & Unit	Group	Pre-test M (SD)	Post-test M (SD)	Retention M (SD)
Spatial Anxiety (score)	All participants	50.0 (11.2)	40.1 (8.5)	43.1 (9.1)
	Males (n=37)	44.7 (9.8)	39.5 (8.6)	41.5 (9.0)
	Females (n=38)	55.3 (10.2)	40.5 (8.4)	44.6 (9.5)
Maze Completion Time (s)	All participants	65.4 (13.0)	47.5 (10.5)	51.0 (11.5)
	Males (n=37)	60.3 (12.0)	45.0 (10.0)	48.0 (11.0)
	Females (n=38)	70.4 (11.5)	50.0 (10.7)	54.0 (12.0)
Depth-Judgment Accuracy (%)	All participants	62.5% (9.0%)	78.6% (8.0%)	76.7% (8.5%)
	Males (n=37)	64.7% (8.0%)	79.5% (7.5%)	78.2% (8.0%)
	Females (n=38)	61.3% (9.5%)	79.5% (7.5%)	75.8% (9.0%)

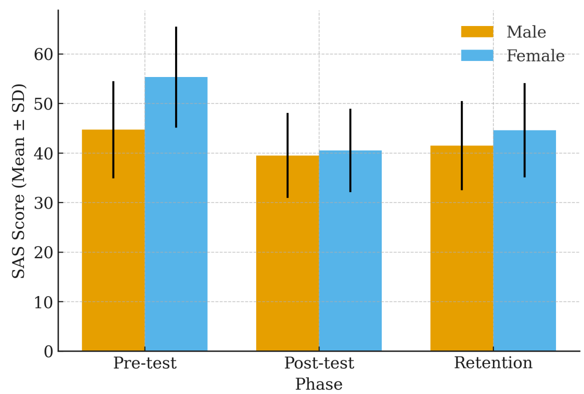

Fig 2. Spatial Anxiety by gender across phases (mean ± SD). Error bars denote SD. N = 75 (male 37, female 38). ***Note:*** *Lower scores show reduced anxiety (improvement)*

Training resulted in a significant and durable decrease in spatial anxiety (21% post-training; 13% at retention), and the baseline gap between women and men became non-significant post-training. This pattern continues recent VR findings by showing anxiety reduction as a designed outcome[16], not merely a by-product, aligning with evidence that anxiety shapes spatial performance and can mediate observed gender differences[20].

3.3 Maze Completion Time

Despite meta-analytic trends favouring men on navigation[9], our study showed large training-driven improvements; Maze time decreased from 65.4 ± 13.0 s to 47.5 ± 10.5 s. At retention, it was 51.0 ± 11.5 s. The male-female comparisons by phase were significant and showed moderate to large effects (pre: $t(72.65)=-3.72$, $p=0.0004$, $d=-0.86$; post: $t(72.88)=-2.09$, $p=0.040$, $d=-0.48$; retention: $t(72.74)=-2.26$, $p=0.027$, $d=-0.52$). The gap was smaller after training (Figure 3).

The similar and significant speed improvements in both groups achieve our efficiency goal. This contrasts with fixed-level studies, where speed improvements may not be applicable. Here, retention was maintained, and the gender gap decreased, remaining statistically detectable. This is consistent with reports that task demands and stress can alter strategy in immersive VR and that calibration can mitigate these effects[18]. The nearly 27% speed increase with retention (approximately -19.6% compared to the baseline at two weeks) contrasts with fixed-level studies, which show immediate but unstable speed improvements[1]. The fact that both genders improved together while the baseline gap decreased indicates that the adaptive training helped improve the strategy during immersive (suggesting that managing layout complexity helped stabilize strategy during immersive demand. This aligns with studies that show load-driven increases in spatial anxiety[11]), stressful situations. This finding aligns with recent evidence from VR studies[18]. These findings indicate that the spatial training substantially improved maze navigation speed for all participants, with females showing as much improvement as males and effectively catching up to near parity by the end of the study.

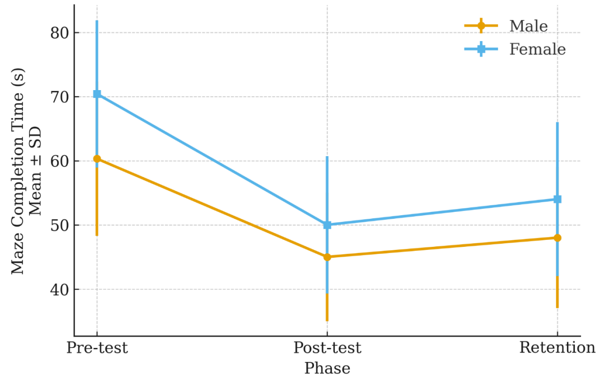

Fig 3. Maze completion time by gender across phases (mean ± SD). Error bars denote SD. N = 75. ***Note:*** *Lower times show faster navigation (improvement)*

3.4 Depth-Judgment Accuracy

Accuracy increased from 62.5% ± 9.0% in the pre-test to 78.6% ± 8.0% in the post-test and remained at 76.7% ± 8.5% during retention (Figure 4). Male-female differences were moderate in the pre-test (t(72.92)=2.36, p=0.021, d=0.54) but not significant in the post-test and retention (post: t(71.75)=0.90, p=0.371, d=0.21; retention: t(72.09)=1.46, p=0.149, d=0.34).

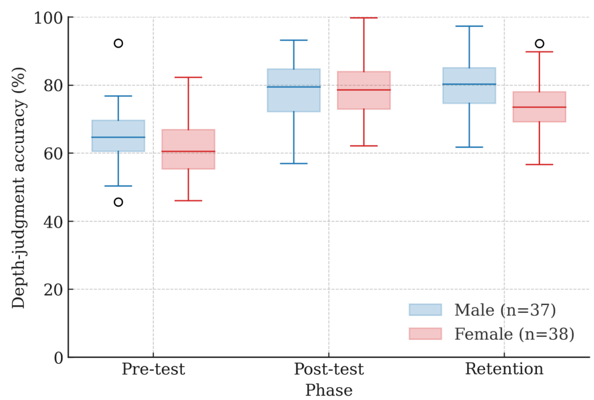

Fig 4. Depth-judgment accuracy (%) by gender across phases (mean ± SD). Error bars denote SD. N = 75. ***Note:*** *Higher percentages show improved accuracy*

In particular, we resolved the precision–accuracy tension [5] reported for stereoscopic game exposure [3] by delivering an actual accuracy improvement (+15.7 points) that continued at two weeks (+9.9 points), extending proof-of-concept depth-training reports to a larger, within-subject design with standardised outcome tests [12]. With uneven results and inconsistent metrics in previous research [1], we addressed these gaps by achieving navigation efficiency and practical accuracy, thereby separating adaptive practice from fixed gold-standard tests and incorporating a retention phase [17]. Unlike personalised game training, which often raises speed or score without improving perceptual reliability [2], our study delivered a 26.9% improvement in depth-judgment accuracy. Building on small-sample stereovision pilots [3], we showed durable improvements on standardised tasks in a larger, within-subject group. Our study on calibration addressed the precision-accuracy mismatch in stereoscopic gaming, where precision can increase without corresponding improvements in accuracy [4]. By adjusting depth perception and layout complexity trial-by-trial, participants achieved a 26.9% increase in depth-judgment accuracy that remained +17.0% above baseline at two weeks, indicating that real-time difficulty control aligned cue sampling with current skill and avoided both under- and over-challenge. Previous studies on VR showed that spatial anxiety can be reduced in navigation settings. Still, few interventions treat anxiety reduction as a co-primary endpoint [5]. Our study provides evidence that anxiety dropped 21% immediately and stabilised 13% below baseline at retention [13] and also provides evidence that anxiety mediates sex differences in spatial performance and motivation shapes uncertainty of learning in general [21]. This pattern of increased adaptive training, which holds task demand within the stipulated time, will limit overload and reduce the difficulty of spatial tasks [18].

High spatial perception processing can stress working memory [8]; our study supported more effective encoding and decision-making. A 25.6% drop in maze time and a 26.9% rise in depth accuracy suggest genuine increased trends [22]. Meta-analytic work shows that gender differences in spatial performance often persist into adulthood [9]. In our study, the initial gaps in anxiety and performance decreased at post-test. They remained smaller at retention, consistent with the idea that calibrated difficulty and explicit anxiety targeting can narrow disparities that would otherwise exist [21]. Although prior perceptual-learning studies reveal plasticity even in seniors, they rarely pair navigation with depth judgment [10]. Our multi-component, adaptive design, therefore, highlights the increase, with clear relevance for STEM training and related applied settings [19]. Accuracy increased by 15 to 18 points after training and remained approximately 10 points above the baseline during retention. This extended earlier proof-of-concept stereovision training to a larger sample within participants using standardized outcome tests [3]. In contrast to previous stereoscopic game exposure, which improved precision but not accuracy, the current closed-loop protocol produced a considerable improvement in accuracy [5]. The strength of improvements likely reflects three design choices: using non-identical parallel forms at retention to encourage transfer rather than memorization, allowing calibrated exercise to combine and stabilise depth-cue weighting, and reducing anxiety so later sessions faced less cognitive interference. Overall, these foundations recognise the need for longer-horizon, multi-metric evaluation in adaptive VR training [1]. Recent studies on eye-tracking biofeedback work further highlight the translational potential of targeted VR training [23].

4 Conclusions

A closed-loop depth calibration can improve perceptual accuracy by 26.9%, reduce navigation time by 25.6%, and lower spatial anxiety by 21% immediately and 13% over time on non-adaptive tests. This approach meets the need for multi-metric and lasting results in the field [16]. By adjusting difficulty in real time and considering emotions as an important factor, the design balances precision with accuracy, reduces baseline gaps, and provides a useful model for training spatial skills. In conclusion, these results extend recent reports by indicating strong improvements across affect, navigation efficiency [24], and perceptual reliability, the very combination that many prior studies did not evaluate in performance.

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