Impact of Different Field-of-Views on Visuospatial Memory and Cognitive Workload in a Complex Virtual Environment

Akash K. Rao, Ronnie V. Daniel, Vishal Pandey, Sushil Chandra, and Varun Dutt

Abstract The evolution of state-of-the-art visual interfaces incorporating 360° video feeds has paved the way in expanding the human's capacity to sense complex environments exponentially. As the horizontal field-of-view (FoV) of an adult healthy human being is limited, it is imperative to evaluate the human-perceptual cognitive functions (like visuospatial working memory) as a function of FoVs offered by different visual interfaces. This research's primary objective is to address this need and to investigate the influence of different FoVs on cognitive performance in a complex virtual environment. In a laboratory-based experiment, 60 healthy subjects were equally and randomly divided into three between-subject conditions: 180° × 2 FoV (interface divided into an upper section projecting a front view of 180° and a lower section projecting a back view of 180°); 360° × 1 FoV (panoramic); and the 360° × 90° FoV (panoramic view in the lower section of the interface and 90° view of the region of interest in the upper section, which could be panned as per the participant's convenience). Participants were initially asked to place six mines at six different locations of their choice within 5 min. Starting from a different initiation point in the virtual environment, participants were then asked to specify the mines' approximate location within 5 min. Behavioral and cognitive workload results revealed that participants performed better and perceived lesser workload requirements in the 180° × 2 FoV and the 360° × 90° FoV condition compared to the 360° × 1 FoV condition. We highlight the implications of this research for creating compelling and reliable virtual environments for training personnel.

Keywords 360° visual interfaces · Fields-of-view · Visuospatial memory · Cognitive workload · Decision making · Virtual environments

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1 Introduction

The rapid evolution of technology has empowered our propensity to sense complex, three-dimensional environments at a distance. This augmentation of our capacity is very important, especially for facilitating cognitive processes like visual perception, visual encoding, visual information processing, and subsequent action translation. But the meticulous and systematic extension of such sensory augmentations is crucial, especially in the military context. The design and development of 360° visual interface through image stitching/video transformation has been one such modern augmentation for empowering our perceptual capabilities. According to [1–3], modern 360° visual interfaces enable better spatial allocation of attention and better situational awareness. However, the average horizontal field-of-view (FoV) of a healthy adult human ranges from 120 to 200° [4]. Hence, viewing the entirety of 360° requires stitching multiple views together or compressing the display horizontally [1, 4]. But, compressing the 360° visual interface horizontally, primarily through image transformation, leads to information loss, negatively influencing the spatial allocation of attention and information perception [5]. Besides, the resulting distortion from compressing the 360° visual interface horizontally interferes with the user's capacity to efficiently perceive the visuospatial relationship between multiple three-dimensional structures in a complex environment [1]. Therefore, stitching various, mutually exclusive FoVs together has been recommended by most researchers [4, 5]. Generic techniques, like combining views from multiple cameras [6] and two-dimensional projective transformations, have been used for this purpose [4]. Preliminary research has evaluated numerous ways to incorporate video from various cameras to produce a continuous 360° visual interface [4, 7–9]. For example, a visual interface with a 90° × 4 FoV was compared to an interface with a 180° × 2 FoV in a dynamic decision-making task [4]. Similarly, researchers in [10] investigated the visual interface's efficacy with a 90° × 4 FoV compared to an interface with a 180° × 2 FoV in teleoperated search-and-rescue task [10]. In both cases, it was found out that the visual interface with the 90° × 4 FoV induced high cognitive workload requirements and below-par performance from the participants [4, 10]. Other researchers have also evaluated the efficacy of a panoramic 360° visual interface for intelligence, reconnaissance, and surveillance [11, 12]. According to recent studies, panoramic 360° visual interfaces and visual interfaces with a 180° × 2 FoV are the most viable, reliable methods for conveying 360° information for enhanced cognitive performance. But most of the research concerning these interfaces has been either focusing on target detection [1], formulation of cognitive maps [7], or search-and-rescue [10]. Recent research has also suggested designing and evaluating a visual interface with a 360° × 90° FoV, where the 360° panoramic view is displayed in the lower section of the interface and a 90° FoV of the region of interest is conveyed in the upper section of the interface [8, 13]. This 90° FoV can be panned as per the user's convenience [8, 13]. Even though the researchers have claimed that this visual interface could be the most optimal 360° visual interface designed till present [13], research concerning the perceptual, behavioral, and workload-based ramifications

of such an interface has hardly been investigated in the literature. Besides, research evaluating perceptual-cognitive functions (like visuospatial memory) and the relationship between visuospatial memory and cognitive workload as a function of FoV is lacking and much needed in literature.

Since the horizontal FoV of a healthy, adult human being ranges from 120 to 200° [4], the amount of information acquired through 360° visual interfaces could be perceptually and cognitively intimidating, especially to a novice user [1, 4]. This can be corroborated by theories in perceptual-cognitive performance and decision making like visuospatial allocation of attention theory [14] and instance-based learning theory (IBLT) [15, 16]. According to the visuospatial allocation of attention theory, the visuospatial distribution of attention is more efficient if the 360° visual interface provides easily discernible visual landmarks. This leads to FoV peripheries being directed left or right concerning the participant's heading in the virtual environment, subsequently allocating visuospatial attention better [14]. According to [14], this also leads to optimal utilization of information processing resources in the brain due to the user's propensity to adapt to a more pronounced distribution of visuospatial attention [14]. According to IBLT [15, 16], a well-researched theory on how humans makes decisions from experience, decision making is usually a five-step process. It involves recognizing the situation, the judgment based on the user's experience, the user's choices based on the judgments, translation of the chosen action, and feedback to those experiences that led to the chosen action [15, 16]. Hence, as per IBLT and visuospatial allocation of attention theory, users should find 360° visual interfaces with a 180° × 2 FoV and a 360° × 90° FoV easier to negotiate with optimal cognitive resource utilization compared to the visual interface with 360° × 1 FoV, even though all the interfaces mathematically convey the same amount of information. However, research on the effects of different FoVs offered by 360° visual interfaces on visuospatial memory and cognitive workload in a complex virtual environment is lacking and much needed in literature.

The primary objective of this research is to address this literature gap. Specifically, we design an experiment to evaluate the impact of different 360° visual interface FoVs (180° × 2 FoV, 360° × 1 FoV, and 360° × 90° FoV) on visuospatial memory and cognitive workload in a complex virtual environment. In what follows, we provide a brief overview of research involving 360° visual interfaces and perceptual-cognitive functions. Next, we evaluate three 360° visual interfaces that differed in their FoVs and evaluated human performance and cognitive workload in an experiment. We then discuss the results in the experiment and highlight the inference of our results on visuospatial memory and cognitive workload in tasks involving 360° visual interfaces.

2   Background

A few studies have evaluated higher-level cognitive functions against 360° visual interfaces with variable FoVs in generic virtual environments. For instance,

researchers in [1] assessed the efficacy of three different 360° interfaces in target detection and remote-control task. Participants were made to locate some pre-specified targets in a complex, three-dimensional terrain using a two-dimensional 360° visual interface. Participants initially perceived their respective egocentric directions to targets and later placed them on a digitally reconstructed overhead view of the complex terrain. The results indicated that non-seamless interfaces, i.e., interfaces with discernible visual boundaries, facilitated better spatial understanding.

Similarly, researchers in another study [4] investigated the influence of two different FoVs (90° × 4 FoV and 180° × 2 FoV) and two different proportions of targets and distractors (80–20% and 20–80%) in a search-and-shoot task. Twenty-five participants executed all four different FoVs and proportions of targets and distractors scenario in random order. Results suggested that participants performed better and perceived lesser cognitive workload in the 180° × 2 FoV condition compared to the 90° × 4 FoV condition regardless of the proportions of targets and distractors in the virtual environment.

Researchers in [17] highlighted the importance of investigating the relationship between operator capabilities, operational needs, and the operator's inherent cognitive ability to retrieve and process complex information coming from visual interfaces with 360° sensors. They investigated a set of evaluation criteria crucial for the maintenance of 360° situational awareness in complex military environments. They also highlighted the need for the 360° visual interface designs to conform to the individual's neurocognitive processing capability, which would subsequently enhance human performance.

Researchers in [13, 18] designed and proposed the possibility of a scalable, high-fidelity visual interface with a 360° × 90° FoV for a manned ground vehicle for maintaining optimal local area awareness in complex, three-dimensional terrains. As explained in Sect. 1, this design consisted of a 360° panoramic view displayed in the lower section of the interface and a 90° FoV of the region of interest displayed in the upper section of the interface [13, 18]. This 90° FoV can be panned as per the user's convenience. The researchers in [18] then evaluated this visual interface's efficacy by comparing it to the traditional 90° × 4 interface. The visual interface with the 360° × 90° FoV significantly outperformed the conventional 90° × 4 interface on all accounts (behavioral, perceptual, and workload). But an evaluation of its efficacy with more optimal 360° interfaces (180° × 2 FoV, 360° × 1 panoramic) has hardly been documented and much needed in literature.

As per the visuospatial allocation of attention theory [14] and IBLT [15, 16], we expect the participants to perform better in the 180° × 2 FoV condition and the 360° × 90° FoV condition compared to the 360° × 1 FoV condition. Also, owing to its FoV, which is comparable to the healthy adult horizontal FoV, we expect the participants to perceive lesser cognitive workload requirements in the 180° × 2 FoV condition.

3 Materials and Methods

3.1 Participants

A total of 60 participants (21 females and 39 males, mean age $=$ 21.4 years, standard deviation $=$ 2.1 years, minimum age $=$ 19 years, maximum age $=$ 26 years) at the Department of Biomedical Engineering, Institute of Nuclear Medicine and Allied Sciences, Delhi, India and the Indian Institute of Technology Mandi, Himachal Pradesh, India, participated in this study. An institutional ethical committee approved the study at the Institute of Nuclear Medicine and Allied Sciences and the Indian Institute of Technology Mandi. Participation in the study was voluntary, and the subjects gave written consent before participating in the study. Out of 60 participants, 56 participants were right-handed, 3 participants were left-handed, and 1 was ambidextrous. None of the participants reported neurological/psychological/mental history of any kind. All the participants hailed from a science/engineering/technology/mathematics (STEM) background. None of the participants had experienced a 360° visual interface before. All the participants received a flat payment of INR 50 irrespective of their performance in the study. The participants were also paid an additional INR 50 if they completed all the objectives in the study within the given time frame, i.e., 5 min.

3.2 The Virtual Environment

A ground-based virtual environment was designed for the desktop screen using Unity3D version 2019.2.3f1 [19]. Some of the 3D avatars incorporated in the virtual environment were created using Blender3D version 2.80 [20], and some of them were directly imported from the Unity3D asset store. Three different virtual environment versions were designed: 180° × 2 FoV, 360° × 90° FoV, and 360° × 1 FoV. A detailed explanation of each FoV condition is given in Sect. 3.1. The virtual environment consisted of two phases: the mines placing phase and the mines locating phase. In the mines placing phase, the participants were asked to place six mines at distinctly different locations (of their choice) in the virtual environment. The participants were not allowed to place the mines very close to each other. The virtual environment was programmed to indicate through an audio-visual stimulus (a beep along with a red light) if the Euclidean distance between two mines (i.e., a mine placed and a mine which was currently being placed by the participant) was less than 50 Unity3D units (1 Unity3D unit could be roughly approximated to 1 m in the real world). All the participants were given 5 min to complete the mines placing task. However, participants could switch to the mines locating task as soon as they finished the mines placing task. Several 3D objects (like cows, tents, barrels, and ropes) were placed randomly in the virtual environment so that participants could use them as landmarks (see Fig. 1). In the mines locating phase, all participants would start from a different
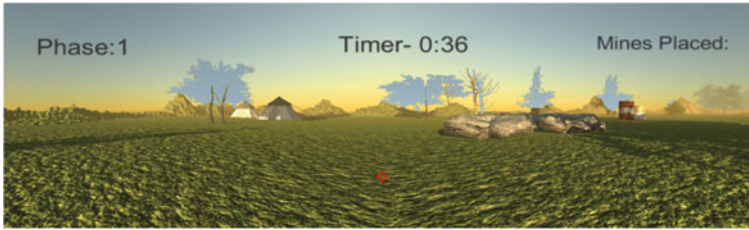
Fig. 1 Front view of the virtual environment. The number of mines placed was indicated in the top-right corner of the interface. The timer (in seconds) was placed in the top-central corner of the interface. The virtual environment phase was indicated in the top-left corner of the interface

initiation point (i.e., a point in the virtual environment that was randomly decided and one that was different from the point of beginning of the mines placing task). Participants were asked to point to the approximate location of the mines they had initially placed in no particular order. Participants were given 5 min to complete the mines locating phase. If participants could not complete the task within the stipulated time frame, the virtual environment would automatically terminate at the end of 5 min. The virtual environment was executed on a 24 inch workstation computer at a resolution of 1920×1080 pixels. Participants used a Logitech Extreme 3D Pro joystick to navigate the virtual environment and to place/locate the mines. The study was conducted in an isolated room, devoid of any external interference/noise.

3.3 Experiment Design

In a laboratory-based experiment, 60 healthy participants were divided equally and randomly into three between-subject conditions: the $180° \times 2$ FoV condition, the $360° \times 1$ FoV condition; and the $360° \times 90°$ FoV condition (see Fig. 2). As shown in Fig. 2, all the participants undertook an acclimatization session for approximately 5 min, where they got familiar with the immersion, resolution, and navigating in a dummy virtual environment using the 3D controller (see Fig. 2).

In the $180° \times 2$ FoV condition, the interface was divided into an upper section projecting a front view of $180°$ and a lower section projecting a back view of $180°$ (see Fig. 3a)). This FoV condition was designed based on the approximate horizontal FoV of a healthy human, as suggested by [4]. In the $360° \times 1$ FoV condition, the interface was a continuous panoramic image (see Fig. 3b). According to [3, 4], this interface reduced the load on human visuospatial processing since two $180°$ views are stitched together in the interface. In the $360° \times 90°$ condition, the interface was a panoramic view in the lower section of the interface and a $90°$ view of the region of interest in the upper section, which could be panned as per the participant's convenience (see Fig. 3c). This FoV condition was based on the design initially proposed by [13, 18]. This condition is motivated from the fact that for achieving complete situational
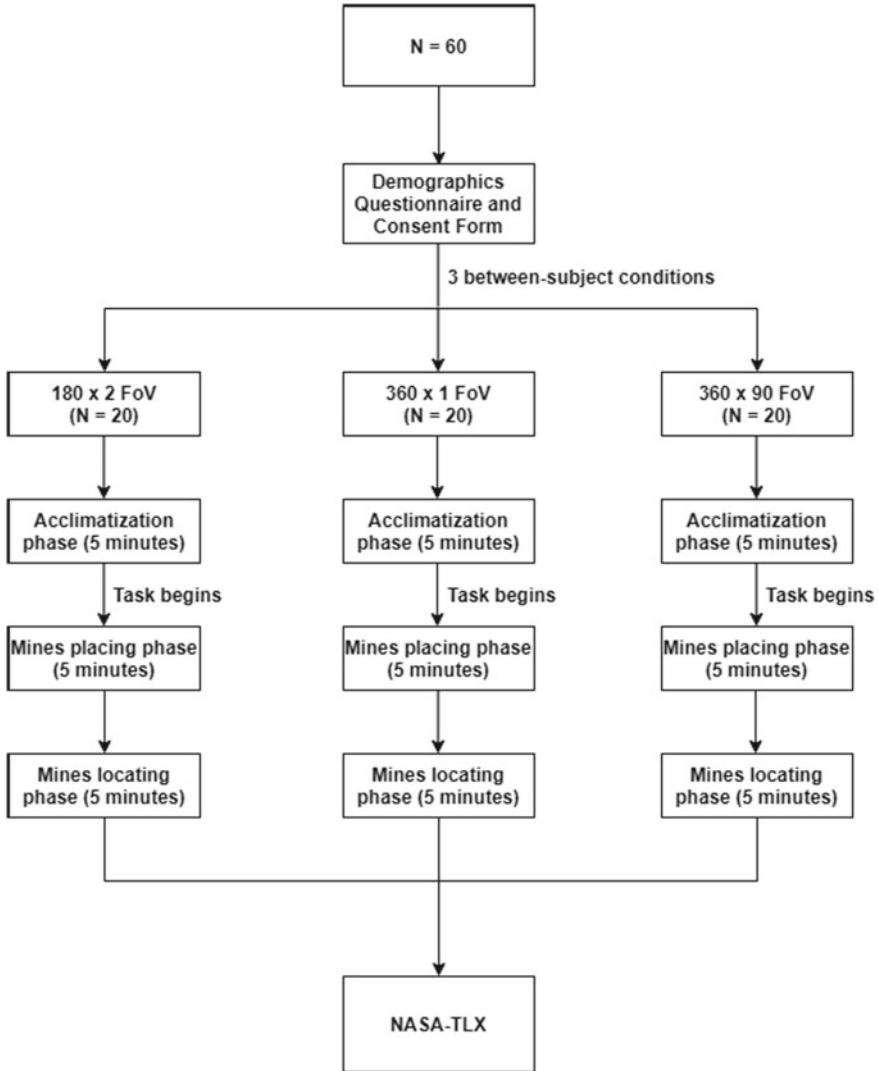
**Fig. 2** Experimental design of the study

awareness, the interface should be able to provide a wholesome picture of the environment and specific regions of interest [18]. The regions of interest could be panned as per the user's convenience. During the task, various performance measures like percentage of mines correctly located, the average time taken (in seconds), and the average Euclidean distance between mines placed and mines located (in Unity3D units, where 1 Unity3D unit equaled 1 m in the real world) were calculated. The percentage of mines correctly located was calculated by dividing the number of mines correctly located by 6 (the total number of mines placed) and multiplying it by
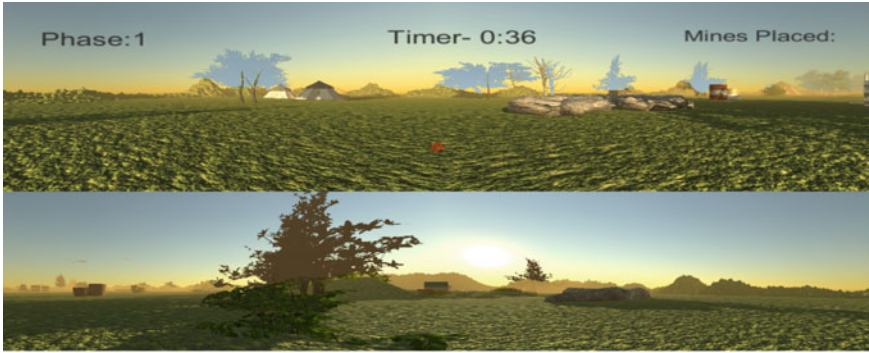
(a)
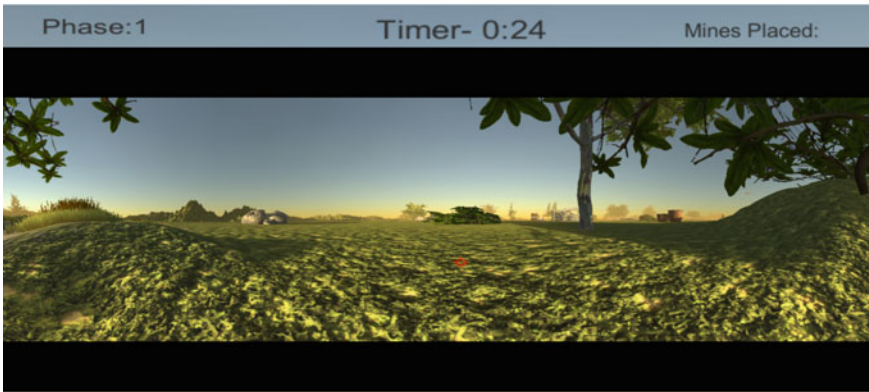
(b)
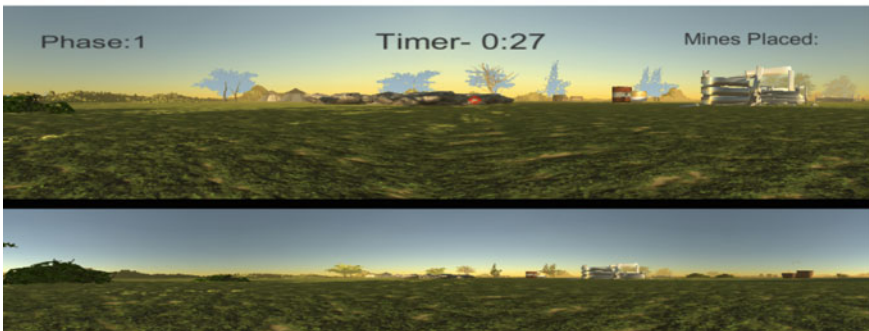
(c)

Fig. 3 Three different FoV conditions used in the virtual environment. **a** The 180° × 2 FoV condition. **b** The 360° × 1 FoV condition and **c** the 360° × 90° FoV condition

100. Each mine located was logged as 'located correctly' if the distance between the mines placed in the first phase and the corresponding mine located in the second phase was less than 10 Unity3D units (~10 m in the real world). The average Euclidean distance (AED) between mines placed and mines located was calculated as follows:

$$\text{AED} = \sqrt{\left(x_{\text{minesplaced}} - x_{\text{mineslocated}}\right)^2 - \left(y_{\text{minesplaced}} - y_{\text{mineslocated}}\right)^2} \quad (1)$$

Besides, participants also undertook a computerized version of the NASA-Task Load Index (TLX) [21]. The NASA-TLX is a widely used self-reported scale for measuring participants' perceived workload on a 100-point Likert scale, with increments of 5 [5]. The NASA-TLX was administered after participants executed both the phases, as shown in Fig. 2. The NASA-TLX was divided into six subscales: mental demand, physical demand, temporal demand, performance satisfaction, effort, and frustration level. We carried out one-way ANOVAs to evaluate the effect of different FoV conditions ($180° \times 2$, $360° \times 1$, and $360° \times 90°$) on various performance and cognitive/workload measures. The alpha level was set to 0.05, and the power was set to 0.8. Overall, on account of IBLT [15, 16] and visuospatial allocation of attention theory [14], we expected the participants in the $180° \times 2$ FoV condition and the $360° \times 90°$ FoV condition to perform better compared to the $360° \times 1$ condition. Also, on account of IBLT [15, 16], effective spatial allocation theory [14], and cognitive load theory [22], we expected the $180° \times 2$ FoV condition to yield lower mental demand and effort requirements and higher-performance satisfaction compared to the $360° \times 90°$ FoV condition and the $360° \times 1$ FoV condition. Since the study did not involve vigorous physical movement/locomotion of any kind and did not incorporate particularly annoying/controversial/irritating stimuli, we did not expect the self-reported physical demand and frustration level to reach statistical significance.

3.4 Procedure

Before the participants began the experiment, they were briefed about the objectives to be achieved. The participants were given detailed instructions on executing both the phases of the experiment: the mines placing phase and the mines locating phase. Participants were also informed that the mines they would place in the mines placing phase would have to be subsequently located in the mines locating phase, beginning the phase from a different initiation point (as described in Sect. 3.2). All the participants then undertook a basic demographics questionnaire and gave their written consent to participate in the study (see Fig. 2).

4 Results

4.1 Performance Measures

Percentage of Mines Correctly Located

Figure 4 shows the percentage of mines correctly located across all FoV conditions. As shown in Fig. 4, the percentage of mines correctly located was significantly different across all FoV conditions ($F(2.59) = 9.61, p < 0.05, \eta_p^2 = 0.74$). Bonferroni post-hoc test revealed that the percentage of mines correctly located was similar in the $180° \times 2$ and $360° \times 90°$ FoV conditions; however, there was a significant difference between the $360° \times 1$ and $180° \times 2$ FoV condition and the $360° \times 90°$ FoV condition ($180° \times 2$ FoV: $\mu = 62.5\% \sim 360° \times 90°$ FoV: $\mu = 61.67\%$ ($p = 0.99$); $360° \times 1$ FoV: $\mu = 31.67\% < 180° \times 2$ FoV: $\mu = 62.5\%$ ($p < 0.05$); $360° \times 1$ FoV: $\mu = 31.67\% < 360° \times 90°$ FoV: $\mu = 61.67\%$ ($p < 0.05$)). Overall, as per our expectations, participants in the $180° \times 2$ FoV condition and the $360° \times 90°$ FoV condition correctly located more mines compared to the $360° \times 1$ FoV condition.

Average Time Taken

Figure 5 shows the average time taken (in seconds) across all FoV conditions. As shown in Fig. 5, the average time taken was significantly different across different FoV conditions ($F(2.59) = 5.08, p < 0.05, \eta_p^2 = 0.84$). Bonferroni post-hoc test revealed that the average time taken was similar in the $180° \times 2$ and $360° \times 90°$ FoV condition and the $180° \times 2$ and $360° \times 1$ FoV condition; however, there was a significant difference between the $360° \times 1$ and the $360° \times 90°$ FoV conditions ($180° \times 2$ FoV: $\mu = 246.55$ s $\sim 360° \times 90°$ FoV: $\mu = 257.95$ s ($p = 0.99$); $180° \times 2$ FoV: $\mu = 246.55$ s $\sim 360° \times 1$ FoV: $\mu = 216.95$ s ($p = 0.09$); $360° \times 1$ FoV: μ

Fig. 4 Means and 95% confidence intervals of the percentage of mines correctly located across different FoV conditions. The error bars show 95% CI across point estimates
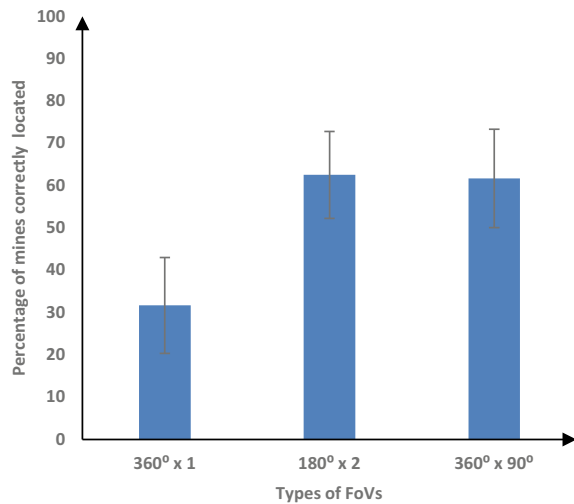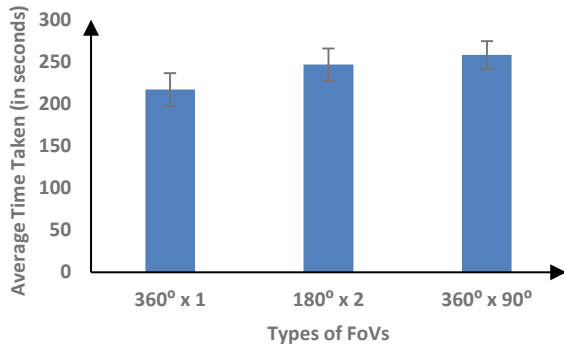
Fig. 5 Means and 95% confidence intervals of the average time taken (in seconds) across different FoV conditions. The error bars show 95% CI across point estimates

$= 216.95$ s $< 360° \times 90°$ FoV: $\mu = 257.95$ s ($p < 0.05$)). Overall, participants in the $360° \times 1$ FoV condition took significantly lesser time compared to those in the $180° \times 2$ and $360° \times 1$ FoV conditions.

Average Euclidean Distance Between Mines Placed and Mines Located
Figure 6 shows the average Euclidean distance between mines placed and mines located (in Unity3D units) across different FoV conditions. As shown in Fig. 6, the average Euclidean distance between mines placed and mines located was significantly different across all FoV conditions ($F(2.59) = 13.81$, $p < 0.05$, $\eta_p^2 = 0.67$). Bonferroni post-hoc test revealed that the average Euclidean distance between mines placed and mines located was similar in the $180° \times 2$ and $360° \times 90°$ FoV condition; however, there was a significant difference between the $360° \times 1$ and $180° \times 2$ FoV condition and the $360° \times 1$ and $360° \times 90°$ FoV condition ($180° \times 2$ FoV: $\mu = 14.3 \sim 360° \times 90°$ FoV: $\mu = 17.25$ ($p = 0.99$); $360° \times 1$ FoV: $\mu = 31.7 > 180° \times 2$ FoV: $\mu = 14.3$ ($p < 0.05$); $360° \times 1$ FoV: $\mu = 31.7 > 360° \times 90°$ FoV: $\mu = 17.25$ ($p < 0.05$)). Overall, as per our expectations, the participants in the $180° \times 2$ FoV condition and the $360° \times 90°$ FoV condition recorded a significantly lesser Euclidean distance between the mines placed and the mines located compared to the $360° \times 1$ FoV condition.

4.2 Workload Measures

Mental Demand
Figure 7 shows the self-reported mental demand across all FoV conditions. As shown in Fig. 7, the self-reported mental demand was significantly different across all FoV conditions ($F(2.59) = 8.54$, $p < 0.05$, $\eta_p^2 = 0.76$). Bonferroni post-hoc test revealed that the self-reported mental demand was significantly different in the $180° \times 2$ and $360° \times 90°$ FoV condition and the $180° \times 2$ and $360° \times 1$ FoV condition; however, the self-reported mental demand was similar across $360° \times 1$ and $360° \times 90°$ FoV condition ($180° \times 2$ FoV: $\mu = 34.75 < 360° \times 1$ FoV: $\mu = 51$ ($p < 0.05$); $180° \times 2$
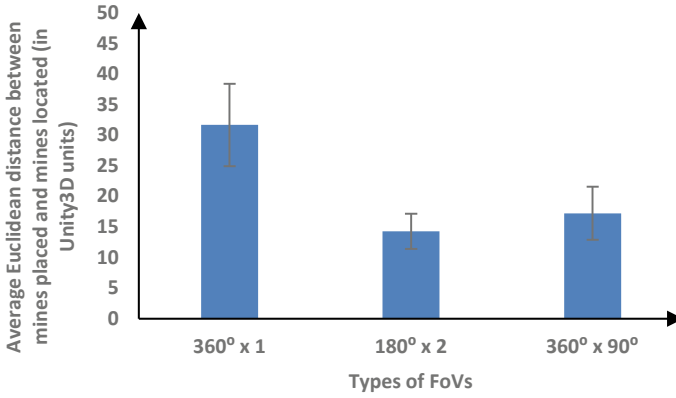
Fig. 6 Means and 95% confidence intervals of the average Euclidean distance between mines placed and mines located (in Unity3D units) across different types of FoV conditions. The error bars show 95% CI across point estimates

Fig. 7 Means and 95% confidence intervals of the self-reported mental demand across different types of FoV conditions. The error bars show 95% CI across point estimates
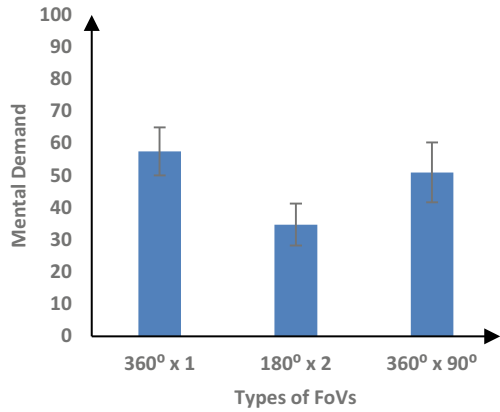

FoV: $\mu = 34.75 < 360° \times 90°$ FoV: $\mu = 57.5$ ($p < 0.05$); $360° \times 1$ FoV: $\mu = 57.5 \sim 360° \times 90°$ FoV: $\mu = 51$ ($p = 0.77$)). Overall, as per our expectations, the $180° \times 2$ FoV condition yielded significantly lesser mental demand requirement compared to the $360° \times 1$ and $360° \times 90°$ FoV condition.

Physical Demand

The self-reported physical demand was not significantly different across different FoV conditions ($F(2.59) = 0.31$, $p = 0.74$, $\eta_p^2 = 0.07$). Since this task did not involve significant muscle/body movement of any kind, the self-reported physical demand's failure to reach statistical significance was conforming to our expectations.

Fig. 8 Means and 95% confidence intervals of the self-reported temporal demand across different types of FoV conditions. The error bars show 95% CI across point estimates
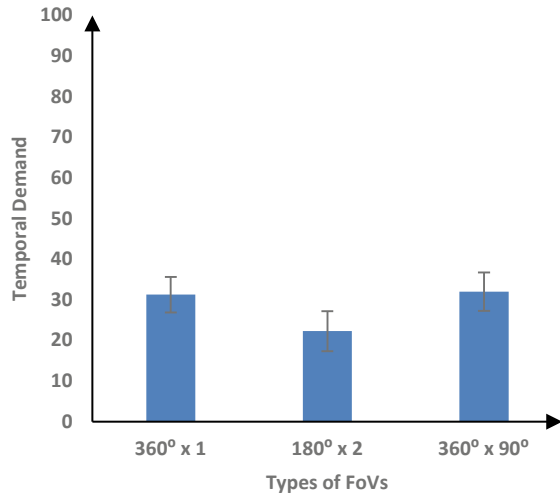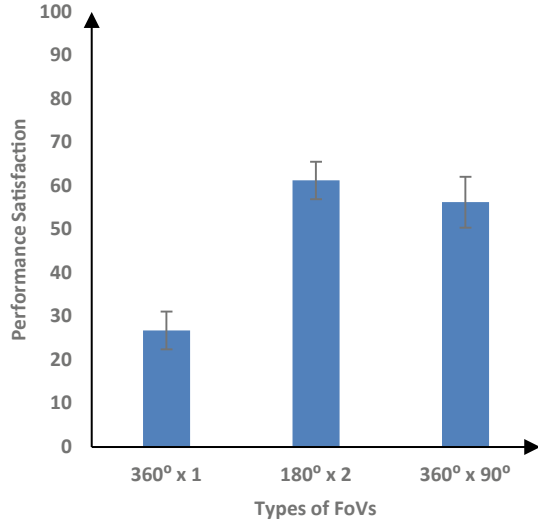

Temporal Demand

Figure 8 shows the self-reported temporal demand across all FoV conditions. As shown in Fig. 8, the self-reported temporal demand was significantly different across all FoV conditions ($F(2.59) = 5.13$, $p < 0.05$, $\eta_p^2 = 0.74$). Bonferroni post-hoc test revealed that the self-reported temporal demand was significantly different in the $180° \times 2$ and $360° \times 90°$ FoV condition and the $180° \times 2$ and $360° \times 1$ FoV condition; however, the self-reported temporal demand was similar across $360° \times 1$ and $360° \times 90°$ FoV condition ($180° \times 2$ FoV: $\mu = 22.25 < 360° \times 1$ FoV: $\mu = 32$ ($p < 0.05$); $180° \times 2$ FoV: $\mu = 22.25 < 360° \times 90°$ FoV: $\mu = 31.25$ ($p < 0.05$); $360° \times 1$ FoV: $\mu = 31.25 \sim 360° \times 90°$ FoV: $\mu = 32$ ($p = 0.99$)). Contrary to the results obtained in average time taken (in seconds) as shown in Fig. 2, as per our expectations, participants in the $180° \times 2$ FoV condition yielded significantly lesser time management requirement compared to the to the $360° \times 1$ and $360° \times 90°$ FoV condition.

Performance Satisfaction

Figure 9 shows the self-reported performance satisfaction across all FoV conditions. As shown in Fig. 9, the self-reported performance satisfaction was significantly different across all FoV conditions ($F(2.59) = 55.29$, $p < 0.05$, $\eta_p^2 = 0.34$). Bonferroni post-hoc test revealed that the self-reported performance satisfaction was similar in the $180° \times 2$ and $360° \times 90°$ FoV condition; however, there was a significant difference between the $360° \times 1$ and $180° \times 2$ FoV condition and the $360° \times 90°$ FoV condition ($180° \times 2$ FoV: $\mu = 61.25 \sim 360° \times 90°$ FoV: $\mu = 56.25$ ($p = 0.49$); $360° \times 1$ FoV: $\mu = 26.25 < 180° \times 2$ FoV: $\mu = 61.25\%$ ($p < 0.05$); $360° \times 1$ FoV: $\mu = 26.25 < 360° \times 90°$ FoV: $\mu = 56.25$ ($p < 0.05$)). Overall, as per our expectations, the participants in the $180° \times 2$ FoV condition and the $360° \times 90°$ FoV condition yielded significantly more performance satisfaction compared to the $360° \times 1$ FoV condition.

Fig. 9 Means and 95%
confidence intervals of the
self-reported performance
satisfaction across different
types of FoV conditions. The
error bars show 95% CI
across point estimates

Effort

Figure 10 shows the self-reported effort across all FoV conditions. As shown in
Fig. 10, the self-reported effort was significantly different across all FoV conditions
($F(2.59) = 12.08$, $p < 0.05$, $\eta_p^2 = 0.69$). Bonferroni post-hoc test revealed that the
self-reported effort was significantly different in the $180° \times 2$ and $360° \times 90°$ FoV
condition and the $180° \times 2$ and $360° \times 1$ FoV condition; however, the self-reported
effort was similar across $360° \times 1$ and $360° \times 90°$ FoV condition ($180° \times 2$ FoV:
$\mu = 38.5 < 360° \times 1$ FoV: $\mu = 64.75$ ($p < 0.05$); $180° \times 2$ FoV: $\mu = 38.5 < 360°$
$\times 90°$ FoV: $\mu = 54.5$ ($p < 0.05$); $360° \times 1$ FoV: $\mu = 64.75 \sim 360° \times 90°$ FoV: μ
$= 54.5$ ($p = 0.19$)). Overall, as per our expectations, the $180° \times 2$ FoV condition
yielded significantly lesser effort requirement compared to the $360° \times 1$ and $360° \times$
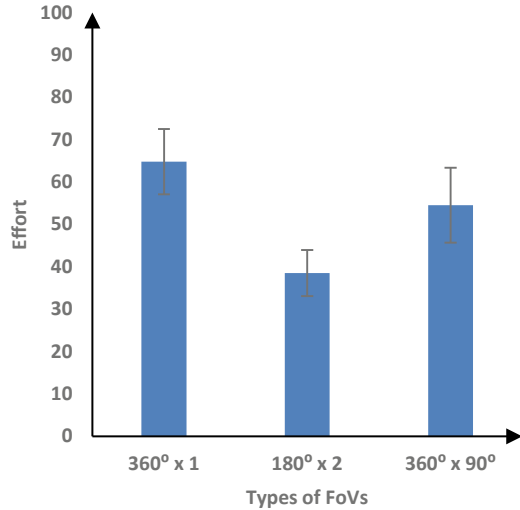$90°$ FoV condition.

Frustration Level

The self-reported frustration level was not significantly different across different
FoV conditions ($F(2.59) = 0.35$, $p = 0.7$, $\eta_p^2 = 0.09$). Since the experiment did not
contain irritating and annoying stimuli of any kind which could potentially upset the
participants, the non-significance of the self-reported frustration level was as per our
expectations.

4.3   Correlation Analysis

In addition to one-way ANOVA, we also performed a two-tailed Pearson correlation
analysis to investigate the relationship between different performance and cognitive
measures in each of the three conditions. In the $360° \times 1$ FoV condition, the average

Fig. 10 Means and 95% confidence intervals of the self-reported effort across different types of FoV conditions. The error bars show 95% CI across point estimates

time taken (in seconds) was significantly positively correlated with the self-reported performance satisfaction ($r(18) = 0.47$, $p < 0.05$). In the $180° \times 2$ FoV condition, the average time taken was significantly positively correlated with the self-reported mental demand ($r(18) = 0.47$, $p < 0.05$). In the $360° \times 90°$ FoV condition, the average time taken was significantly negatively correlated with the self-reported physical demand ($r(18) = -0.67$, $p < 0.01$).

In the $360° \times 1$ FoV condition, the average Euclidean distance between mines placed and mines located was significantly negatively correlated with the self-reported physical demand ($r(18) = -0.5$, $p < 0.05$). Also, in the $360° \times 1$ FoV condition, the average Euclidean distance between mines placed and mines located was significantly negatively correlated with the self-reported effort ($r(18) = -0.45$, $p < 0.05$). Other correlations were not significant.

5 Discussion and Conclusions

This experiment evaluated the impact of 360° visual interfaces with different FoVs on visuospatial memory and cognitive workload in a complex virtual environment. Results revealed that the participants performed better in the $180° \times 2$ FoV condition and the $360° \times 90°$ FoV condition compared to the $360° \times 1$ FoV condition. Results also indicated that participants generally perceived significantly lesser cognitive workload requirements in the $180° \times 2$ FoV condition compared to the $360° \times 90°$ FoV condition and the $360° \times 1$ FoV condition. Correlation analysis also revealed relationships between performance measures and cognitive workload measures in all the FoV conditions. Overall, most of the results were consistent with the visuospatial allocation of attention theory [14], IBLT [15, 16], and the cognitive load theory [22].

First, we found a significantly higher percentage of mines correctly located in the $180° \times 2$ FoV condition and the $360° \times 90°$ FoV condition compared to the $360° \times 1$ FoV condition. Also, we found the participants in the $180° \times 2$ FoV condition and the $360° \times 90°$ FoV condition recorded significantly lesser average Euclidean distance between mines placed and mines located compared to the $360° \times 1$ FoV condition. These results were likely because the discernible visual landmarks and significantly pronounced image peripheries in both the $180° \times 2$ FoV condition and the $360° \times 90°$ FoV condition led to better visuospatial distribution of attention [14]. In accordance with IBLT [15, 16], the participants were able to create a better mental model of the three-dimensional landmarks present in the virtual environment, which eventually led to better creation of instances in memory concerning the mines placed in the first phase.

Second, we found the average time taken in the $360° \times 90°$ FoV condition to be significantly higher compared to the $180° \times 2$ FoV and the $360° \times 1$ FoV conditions. This result agrees with the performance results in these conditions, where spending little time deteriorated performance in $360° \times 1$ FoV condition compared to that in the $360° \times 90°$ FoV condition. In fact, the correlation analyses supported lesser performance satisfaction in the $360° \times 1$ FoV condition and more mental demand in the $360° \times 90°$ FoV condition.

We also found that participants in the $180° \times 2$ FoV condition perceived significantly lesser cognitive workload requirements (lesser mental demand, lesser effort, lesser temporal demand, and more performance satisfaction) compared to the $360° \times 1$ FoV condition and the $360° \times 90°$ FoV condition. This result was in conjunction with the cognitive load theory [22] and the visuospatial allocation of attention theory [14], where it was argued that the $180° \times 2$ FoV condition was close to the horizontal FoV of an adult, healthy human being (120–200°) [4]. This likely resulted in participants perceiving complex information from the virtual environment with optimal cognitive resources utilization in the brain. Even though the participants had performed equally well in the $360° \times 90°$ FoV condition, the presence of a panoramic 360° view of the environment in addition to the 90° region of interest created significantly more instances in the memory, leading to higher information processing and workload requirements.

We also found out that the average Euclidean distance between mines placed and mines located was negatively correlated with both self-reported physical demand and effort in the $360° \times 1$ FoV condition. This result meant that participants had to exert significantly higher physical demand and exert considerably more effort to reduce the average Euclidean distance between mines placed and mines located which could eventually lead to a higher number of mines being correctly located. This result agreed with the visuospatial allocation of attention theory [14], where the absence of clearly distinguishable landmarks and peripheries in the $360° \times 1$ FoV condition led to participants finding it difficult to distribute their attentional resources uniformly in the virtual environment.

Overall, our results indicated that visual interface with a $180° \times 2$ FoV performed significantly better for training participants in complex visuospatial memory-based tasks. However, participants in the novel $360° \times 90°$ FoV condition also performed

well. The higher cognitive workload and information processing requirements in the $360° \times 90°$ FoV could probably be nullified to an extent by imparting heterogenous longitudinal training to the participants.

The results obtained in this research work could be replicable. However, these results may need to be corroborated and cross-validated by appointing personnel to execute complex tasks in real-world terrain. Thus, as part of future work, we plan to integrate the results obtained in this research to test the efficacy of the transfer of virtual environment-based training in real-world settings. We also plan to evaluate different 360° visual interfaces based on various physiological, neuro-physiological, ergonomic, behavioral, and cognitive parameters.

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