Mapping Technological Dimensions of XR-based Cognitive Augmentation Systems

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***Abstract*—Extended Reality (XR) systems enable immersive interaction in hybrid physical-virtual environments, delivering new perceptual and cognitive experiences compared to traditional digital applications. However, research in this area remains fragmented due to the diversity of XR devices and interaction modalities underlying these experiences. This paper analyzes a corpus of twenty-seven scientific articles on XR-based cognitive augmentation through the lens of a framework involving device type and output modality. By using clustering analysis, we identify specific patterns in how these dimensions have been combined in prior XR systems designed for human cognitive augmentation. Our results reveal a strong dominance of head-mounted displays for visual output, while audio and haptics remain underexplored, a finding that reveals new opportunities for future research in this space.**

Keywords—extended reality, XR, cognitive augmentation, technological dimensions, research implications

I. INTRODUCTION

Extended Reality (XR) refers to a wide spectrum of physical-virtual worlds and corresponding technologies to create and render them to users, encompassing Virtual, Augmented, and Mixed Reality (VR/AR/MR) environments. As these technologies mature, they enable new forms of interaction between users and digital information through natural input modalities and highly immersive experiences [1] as well as novel ways for delivering information [2]. In this context, new opportunities arise to support and enhance human cognitive processes with XR, including perception, memory, attention, and decision-making [3]-[6].

Despite an increasing number of works exploring XR for cognitive augmentation [7]-[11], scientific research in this space remains fragmented due to the diversity of XR devices and the corresponding input/output modalities facilitating the augmentation process. Therefore, understanding how current XR technologies can better contribute to augment human cognition and how new technologies should be designed in this regard remains an open question. Prior work has examined XR applications for cognitive training, such as for specific cognitive tasks [2], [4], [7], but has not addressed the technological configurations through which augmentation was achieved. In this paper, we focus on the relationship between XR device type and output modality as two distinct technological dimensions that influence the user experience of cognitive augmentation. In this context, our primary contribution consists in a structured mapping of existing XR-based cognitive augmentation systems and identifying technological patterns as well as underexplored combinations to guide future research in this space. To this end, we analyze a selected set of prior work on XR-based systems designed for cognitive augmentation, identified through a literature search conducted in the IEEE Xplore and ACM Digital Library databases. Our specific contributions are as follows:

- We analyze scientific contributions that apply XR technologies to human cognitive augmentation using a two-dimensional framework specified by *device type* and *output modality*. A clustering analysis of twenty-seven articles in this space revealed research patterns, dominant trends, and unexplored areas.
- Based on our findings, we identify new research opportunities in XR-based cognitive augmentation and outline practical implications for researchers and practitioners; for example, we highlight the potential of haptics for cognitive augmentation in XR.

II. RELATED WORK

A. An Overview of XR Technology

XR is typically defined as a spectrum of immersive technologies encompassing Virtual, Mixed, and Augmented Reality [1], facilitated through a range of input-output devices, such as devices designed to be worn on the body, e.g., head-mounted displays (HMDs) [6], [9], [12], handheld devices, e.g., smartphones and tablets [3], [13], and devices external to the body embedded in the surrounding environment, e.g., video projectors [14]. Among these, HMDs provide immersive experiences by overlaying virtual objects directly within the user's field of view at eye level, with some designs allowing direct perception of the physical world via see-through lenses [6], [12]. Interactions in XR environments are supported with natural input modalities, such as gestures [15], [16], speech, and eye gaze, as well as through handheld devices [17], [18]. Mobile devices enable XR experiences via window-on-the-world perspectives [3], [13], while environmental augmentation systems often rely on body movements for interaction [14].

This technological overview of XR reveals a trade-off between level of immersion and computational requirements, with each hardware configuration presenting distinct technical characteristics that influence its suitability for various cognitive augmentation scenarios [27], [37]. In terms of immersion, HMDs provide a high level of immersion by occupying the user's primary field of view [38]; in contrast, handheld devices, such as smartphones and tablets, offer immersion through window-on-the-world interactions, but benefit from widespread availability and ease of use, as they

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do not require users to employ additional hardware; lastly, environmental augmentation, such as spatial video projection setups, enable collaborative experiences. While this makes them well-suited for multi-user scenarios, their applicability is constrained by their stationary nature [39]. Overall, these trade-offs show how device type and output modality need to be considered together when designing and evaluating XR-based cognitive augmentation systems.

B. Using XR for Augmenting Human Cognition

XR systems have been designed to enhance various cognitive tasks, such as spatial reasoning, memory, and decision-making, creating new ways for providing users with digital information support [19], with applications in medicine and healthcare, industrial operations, aviation, and others [6], [11], [20]. Examples of prior systems include tools for performing endotracheal intubation [20], guiding a drone pallet through a docking station [11], and following audio instructions in a simulated space mission to execute a sequence of actions on a physical control panel [6]. In medical simulations, the integration of specific modalities, e.g., haptics, contributes to the consolidation of procedural skills [20] that require fine sensorimotor coordination.

Cognitive training applications usually target working memory [8], [21] and attention [8], [17], helping users to process and manage additional information while being engaged with the task at hand. Other applications have addressed decision-making [9], [20] and problem-solving [22], where XR visualizations assist with selection of appropriate responses under time constraints. Support for visual and spatial perception [3], [16] enables users to interpret spatial relationships. In this context, HMDs enhance spatial abilities and three-dimensional mental manipulation [23], support cognitive training through active involvement [24], and can lead to superior cognitive performance compared to conventional digital environments [5]. Also, through the integration of electroencephalography (EEG) sensing into HMDs, XR systems can adapt the presentation of the virtual environment according to the user's neurophysiological state; in this regard, rhythmic stimulation was shown to induce brain states associated with cognitive performance in VR [25], while EEG was applied to monitor attention and adapt task difficulty in VR simulators [26]. Cognitive load was also measured based on ocular and physiological data [17], and electromyography (EMG) was integrated to detect facial muscle activity associated with affective states and cognitive effort [7]. Lastly, estimating cognitive load through eye tracking in VR was explored as an objective mechanism for environment adaptation [17].

III. Technological Dimensions for XR Systems

Understanding how XR technologies can support human cognitive augmentation requires a structured lens to consider key characteristics for interaction and perception in immersive physical-virtual environments. In this context, we employ a two-dimensional framework based on *device type* and *output modality* to examine how various XR systems can support or redistribute cognitive load, as follows:

- *Device type* refers to the physical form through which the XR experience is delivered to users, such as HMDs [8], [32] or spatial augmented reality (SAR) systems based on video projections [14]. This dimension aligns with Milgram and Kishino's [27] Reality-Virtuality continuum, which we interpret through both input (i.e., in relation to the extent of presence) and output (i.e., via reproduction fidelity). It also relates to Sweller's [30] cognitive load theory, which suggests that attention switching increases the mental effort required from users, e.g., mobile devices present augmentations as window-on-the-world displays, whereas HMDs overlay content directly onto the user's view of the physical world.
- *Output modality* refers to the sensory channels involved in the immersive experience, such as visual [3], [18], auditory [10], [14], or haptic [20], [28]. This dimension aligns theoretically with Wickens [29] and Sweller [30], which suggest that distributing information across different sensory channels can reduce cognitive load and support more efficient use of the working memory. In this sense, cognitive augmentation benefits from multimodal integration since information is perceived more effectively when distributed across channels rather than concentrated in only one; e.g., while audio assists navigation, haptics provide additional alerts.

IV. Study

A. Design

To identify relevant scientific contributions on XR systems designed for cognitive augmentation, we conducted a literature review in the IEEE Xplore and ACM Digital Library electronic databases using queries applied to the title and abstract fields and the following keywords: "cognitive augmentation," "cognitive support," "cognitive training," "extended reality," "virtual reality," "augmented reality," and "mixed reality", as follows:

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"query": {
"Title" or "Abstract": {(("cognitive augmentation" OR "augmented cognition" OR "augmented human cognition" OR "cognitive support" OR "augmented cognitive" OR "enhanced cognition" OR "enhanced cognitive" OR "cognitive enhancement" OR "cognitive training") AND ("extended reality" OR "virtual reality" OR "augmented reality" OR "mixed reality" OR "XR" OR "VR" OR "AR" OR "MR"))}
"filter": Publication Date: (* TO 26.10.2025)
}
```

Our search returned a total of 160 results, which were relatively evenly distributed across the two sources, with 78 (48.7%) from IEEE Xplore and 82 (51.3%) from the ACM Digital Library, respectively. We then applied the following eligibility criteria to refine the dataset: (EC_1) articles must be peer-reviewed; (EC_2) no duplicates; (EC_3) keywords have to be used in the context of human cognitive augmentation; (EC_4) studies focusing on specific user groups, such as people with cognitive disabilities or impairments, were excluded since our scope was cognitive augmentation for the general user population; and (EC_5) articles have to report the specific XR technologies used as well as information on the output modalities employed for us to apply the analysis of device type and output modalities following the structure of our two-dimensional framework.

After applying the eligibility criteria EC_1-EC_5, we arrived at a final dataset comprising twenty-seven relevant papers, representing 16.9% of the retrieved query results.

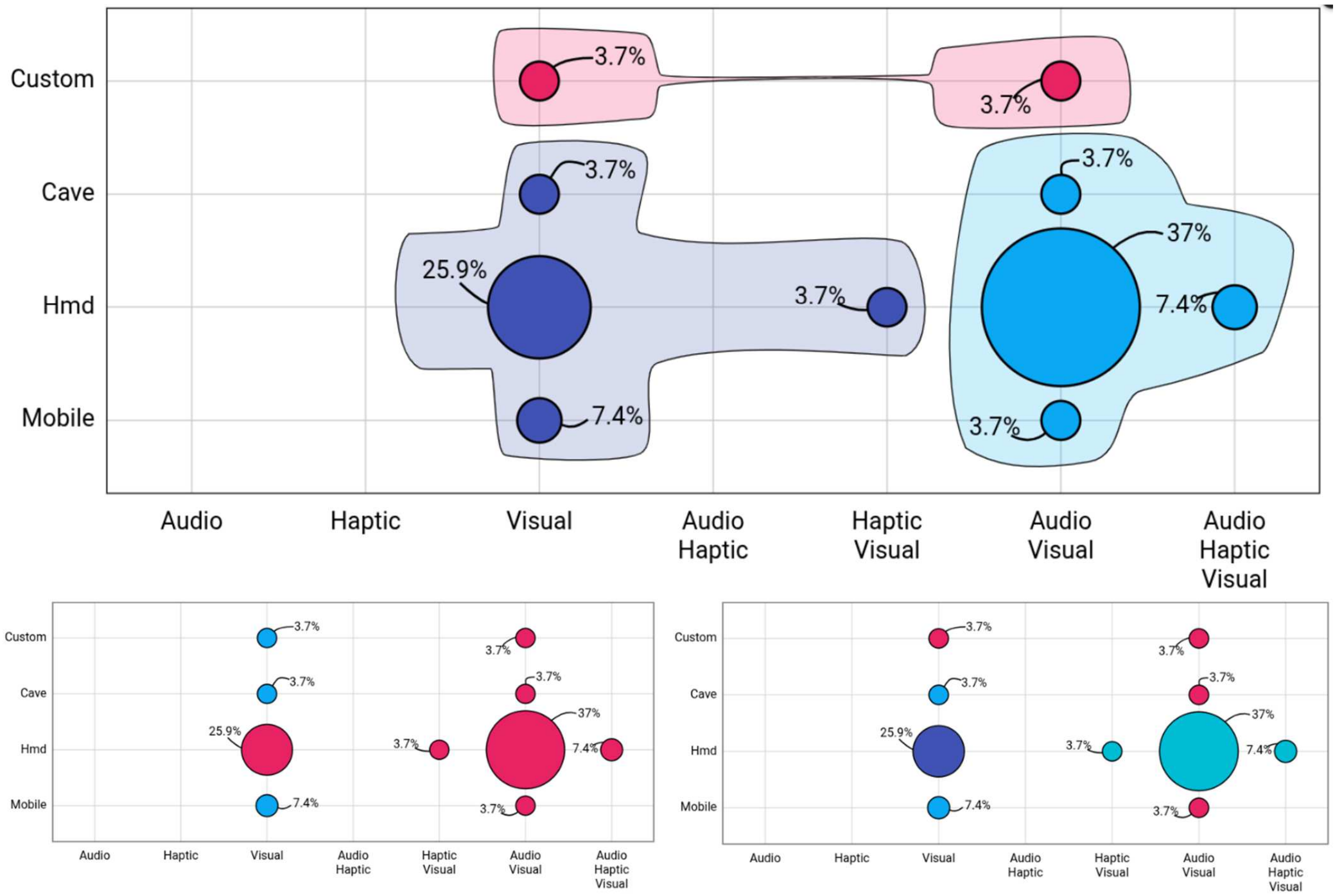

Fig. 1. Visualization of clusters in the device type × output modality space with a 3-cluster solution (top) and preceding/subsequent iterations (bottom).

B. *Data extraction*

From each paper we extracted device types and output modalities according to our two dimensions. For device type, we identified four categories: *head-mounted displays, mobile devices*, *Cave Automatic Virtual Environments (CAVEs)*, and *custom* prototypes. This generic categorization reflects how XR technologies reported in the scientific literature are not tied to a single hardware platform; for example, Unity, one of the most popular platforms for XR development, enables deployment across multiple platforms and devices and, thus, the same application can run on different hardware within the aforementioned categories. Furthermore, these categories describe the extent to which an XR device relates spatially to the user's body, from wearables to devices that are held and to systems external to the body. For the output modality, we identified *visual*, *auditory*, and *haptic* feedback as well as *mixed* categories representing various combinations thereof; for the latter, we treated modality as a multi-label dimension.

C. *Analysis*

To uncover patterns in how device types and output modalities have been combined in the XR systems from the scientific literature, we performed a categorical clustering analysis using the k-medoids algorithm and a custom distance function based on the Jaccard index. Specifically, for each pair of XR systems x and y, we computed their dissimilarity $d(x, y)$ per each dimension, as follows:

$$J_i(x,\, y) \;=\; \frac{|x \cap y|}{|x \cup y|}, \qquad d(x,\, y) \;=\; 1 - \frac{|x \cap y|}{|x \cup y|} \tag{1}$$

For example, assume x is the system proposed in [3], which uses a mobile device and visual output, and y the system proposed in [20], employing an HMD and delivering visual, audio, and haptic feedback. The device type dissimilarity is $d_1 = 1$ because the two systems use different devices. In terms of output modality, the systems share one out of a total of three modalities and, thus, the corresponding dissimilarity on this dimension is computed as $d_2 = 1 - 0.33 = 0.67$.

The final dissimilarity between any two data points in our set combines the two dimensions, as follows:

$$d(x,\, y) \;= w \cdot d_1 + (1-w) \cdot d_2 =$$

$$= w \cdot \left(1 - \frac{|x_1 \cap y_1|}{|x_1 \cup y_1|}\right) + (1-w) \cdot \left(1 - \frac{|x_2 \cap y_2|}{|x_2 \cup y_2|}\right) \tag{2}$$

where w is a weight between 0 and 1 corresponding to the relative importance of the device type compared to the output modality. In our analysis, both dimensions were considered equally important ($w = 0.5$), but further analyses may consider different perspectives. With this parametrization, the values of $d(x, y)$ range from a minimum of 0.0 (corresponding to the case of identical devices and output modalities) to a maximum of 1.0 (no similarity across either device type or output modality). Resuming our example, the dissimilarity between the systems in [3] and [20] is:

$$d(x, y) = 0.5 \cdot 1 + 0.5 \cdot 0.67 = 0.835$$

Had the second system not provided visual feedback, the dissimilarity value between the two would have reached 1.0. This analysis method allowed us to identify the most frequent combinations of devices and output modalities used for cognitive augmentation, which we discuss next.

V. RESULTS

Fig. 1, top shows the results of the clustering analysis. Overall, we found a strong dominance of HMDs along the horizontal axis (device type), which were employed in 77.7% of the systems from our dataset. The other device categories were less represented and appeared only in a small number of cases, e.g., mobile XR used for cognitive augmentation accounted for 11.1%, CAVEs for 7.4%, and custom designs, such as employing video projections, appeared in only one paper, representing 3.7% of the dataset. For example, Meta Quest was used for developing XR games with visual output [18], but also for visual-haptic feedback [31]; HoloLens was employed for AR applications to simulate new environments [6] and overlay layers of digital data on the physical world [9]; VR HMDs, such as HTC Vive, were used to support memory games with either visual [7], [12] or audiovisual [4] feedback, as well as in medical training with audiovisual and haptics [20]. Other HMDs, such as Oculus and Valve Index, were applied in construction simulations [24] and sports training [32], [33]. Less common, CAVEs have been used in construction-based [34] and music-related games [10], while mobile devices were used for AR applications in situated learning [13] and contextual exploration [35].

With respect to the output modality dimension, visual output was present in all systems in the dataset. However, the integration of additional modalities varied, e.g., 40.7% of the work employed visual output only, 48.1% combined visual and audio for cognitive augmentation, e.g., [10], [35], [36], whereas haptic feedback was used in just a small subset of the examined systems, either in combination with visual (3.7%) or audiovisual (7.4%) output [20], [28], [31].

Based on these results, three main clusters of XR systems emerged for cognitive augmentation. To arrive at this specific configuration, we examined both the preceding and succeeding configurations, as follows: going from one to two clusters ($k = 2$), see Fig. 1 bottom-left, resulted in a very large improvement (40.5%), while adding a third cluster ($k = 3$) further reduced within-cluster dissimilarity (27.2%); after three clusters, adding more groups ($k = 4$) resulted in small improvements only (see Fig. 1, bottom-right), which was an indicator that the main structure of the data had already been captured with three clusters (Fig. 1, top).

The largest cluster (shown in light blue in Fig. 1, top) consists primarily of XR systems delivering audiovisual feedback, occasionally complemented by haptic cues. It encompasses HMDs with audiovisual capabilities, HMDs with additionally integrated haptics, mobile devices, and CAVE systems with audiovisual feedback. The second cluster (dark blue) comprises XR systems that rely mainly on visual feedback, with occasional augmentation offered through other modalities, and is primarily associated with HMDs. The third cluster (pink) contains custom XR system designs and prototypes. Despite the wider extent on the horizontal axis (corresponding to visual and audiovisual feedback), the defining characteristic of this cluster is represented by custom technological approaches, e.g., retroreflection and pico-projector setups delivering audiovisual output [14]. These results show that current research is characterized by a limited number of recurring technological configurations, with HMDs emerging as the dominant device type for XR-based cognitive augmentation applications, primarily delivering audiovisual feedback.

VI. DISCUSSION

Our literature review revealed a clear trend toward HMD-based audiovisual solutions for XR systems designed for cognitive augmentation, exposing several gaps in our two-dimensional space of technological design possibilities. In the following, we use our findings to outline implications for XR systems and future research opportunities.

Our analysis revealed several underexplored areas in current research on XR-based cognitive augmentation, which represent opportunities for both researchers and practitioners. In the context where HMDs dominate XR-based cognitive support and training, other technological configurations have still to be explored. For example, researchers should further explore projector-based systems [14] or CAVE installations [10], [34], which may support cognitive augmentation in new contexts where technology is integrated within the surrounding physical environment. Such alternative setups could provide new insights into how XR can support cognitive augmentation across different contexts of use and levels of user engagement. Mobile devices also remain underexplored in XR-based cognitive augmentation [3], [13] despite their widespread use. Compared to HMDs, they are easier to integrate into everyday activities. However, mobile devices offer lower levels of immersion, but their built-in sensors and capacity to combine audio and haptic feedback make them a practical option for implementing XR systems.

Although visual output was present in all systems analyzed in our study, the integration of additional modalities toward multimodal output remains limited. This creates opportunities to explore new forms of cognitive support, such as through tactile and kinesthetic feedback serving as cognitive enhancements where physical cues support spatial understanding, task guidance, or motor learning. As XR devices increasingly capture diversified user input, such as movement, eye gaze, neural activity, or facial expression, they can access an extended model of cognition, in line with Milgram and Kishino's [27] requirements for larger extent of world knowledge in system world modeling. As a result, multimodal output [20], [28] should be considered in the design of XR applications for cognitive augmentation as it may potentially enhance user engagement and support more effective interactions within XR environments.

The technological gaps we identified point to several future work directions. First, research is recommended to understand how different XR technological configurations influence specific cognitive processes, such as attention, memory, spatial reasoning, or decision-making. Examining how device types and output modalities relate to cognitive functions may also contribute to a better understanding of how XR environments can be designed to support cognitive augmentation. Lastly, future studies should explore the long-term use of XR for cognitive support: whereas prior work has focused on short experimental sessions, research is needed to understand how sustained use of XR may affect cognitive performance. The framework proposed in this paper can be used as a comparative instrument for evaluating newly developed XR systems in relation to prior work. For example, by positioning future designs within this space, researchers could easily assess whether they reinforce current trends or explore less investigated configurations.

VII. CONCLUSION

In this paper, we reviewed scientific contributions on XR technologies applied to human cognitive augmentation, which we clustered in a two-dimensional space defined by device type and output modality. Our analysis revealed a dominant pattern with a strong dominance of HMDs and visual output, while audio and haptic modalities remain little explored. Based on these results, we discussed opportunities for future research toward alternative XR technological configurations and multimodal interaction design.

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