

XRCES: A Multidimensional Instrument for Assessing Cognitive Extension in Extended Reality

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Abstract—XR technologies are increasingly used in simulation and education, but research has primarily focused on developing systems without consistently quantifying the extent to which underlying cognitive processes are applied by users and enhanced in XR. To address this, we introduce the XR Cognitive Extension Scale (XRCES), a multidimensional instrument with 18 Likert-scale items organized into 7 dimensions, to assess cognitive extension resulting from user immersion and engagement in XR. We also present empirical results from an evaluation conducted with $N=48$ participants in a STEM learning context to compare XRCES scores for two different durations of user engagement.

Index Terms—Extended Reality, XR, Cognitive Extension, Evaluation, Experiment, Augmented Reality

I. INTRODUCTION

Extended Reality (XR) technologies are increasingly applied in training and education. However, most studies rely on usability or cognitive load assessments without an in-depth analysis of the underlying cognitive processes supported or enhanced by XR immersion. For example, cognitive extension theory [1], [2] suggests that technology can become an integral part of human cognition by influencing key cognitive functions. Nevertheless, this aspect has received limited attention in past XR research, which has focused primarily on developing functional XR prototypes. Assessing XR systems predominantly or solely in terms of usability [3], workload [4], or task performance [5] does not fully explain whether these technologies can extend users' cognitive processes.

In this context, there remains a lack of instruments for cognitive assessment and training in XR [6], such as aspects of perception, memory, attention, embodiment, thinking, integration, and the sustained use of cognitive resources afforded by immersion and engagement in XR environments. To this end, we present in this paper the following practical contributions:

- XRCES, the XR Cognitive Extension Scale, a dedicated multidimensional instrument comprising 18 items organized into 7 dimensions, for assessing different facets of cognitive extension during XR immersion.

- Empirical results from a between-subjects experiment involving $N=48$ participants, in which we applied XRCES to compare cognitive extension for different durations of XR immersion. Our findings indicate a significant effect of immersion duration on perceived cognitive extension, with XRCES scores increasing by 25% on average.

II. RELATED WORK

A. Cognitive Support and Training in XR

XR has become increasingly used for cognitive training and cognitive augmentation due to its ability to influence perception and action through enhanced feelings of immersion and presence. For example, XR environments can increase user engagement for improved learning outcomes [1], [2]. In this context, XR technologies have been explored to support basic cognitive functions, such as attention, memory, and spatial perception, as well as higher-order functions, including decision-making, problem-solving, and creativity [3], [7]–[12]. At the same time, other research [13] has shown that VR-based instruction may evoke higher perceived enjoyment and presence than video-based training, without significant differences in procedural knowledge acquisition; the authors concluded that the value of VR simulations for science learning depends on how they are integrated in the learning process and does not automatically arise from VR immersion. González-Erena et al. [6] reported on challenges for XR-based cognitive assessment and training, such as multimodal feedback integration.

Users can engage in complex scenarios where they develop critical thinking skills [14], with empirical studies showing that virtual reality (VR) environments can positively influence critical thinking development, especially when combined with real-world physical training [15], [16]. In parallel, computational thinking, which involves abstraction, decomposition, and algorithmic reasoning, can be trained as well in XR environments [17]–[19]. Recently, Vatavu [20] proposed extended thinking, a complementary concept to both critical and

computational thinking that is required for effective operation in XR. Extended thinking comprises three dimensions: (1) the world dimension, concerning reasoning about the nature of the XR environment and one's presence within it; (2) the object dimension, concerning reasoning about the nature of objects and the experiences they enable; and (3) the traversing dimension, concerning reasoning about transitions across different XR environments and object representations. However, extending thinking has not yet been formally operationalized through a dedicated assessment instrument.

B. Cognitive Theories and XR

Several cognitive theories can be used to explain how users process virtual content and interact within XR environments. For example, Cognitive Load Theory [19] has been assessed using NASA TLX [21], with studies reporting that STEM training in augmented reality (AR) can significantly reduce cognitive load while improving task execution accuracy [4]. The Circumplex Model of Affect [22], commonly operationalized through the valence-arousal space, has been used to examine users' emotional states and affective responses during XR interactions [5], [23], while Bloom's taxonomy [24] has been applied in educational contexts to analyze learning levels. Lastly, the 4E cognition framework [25], comprising embodied, embedded, enacted, and extended cognition, offers a broader perspective for understanding interactions in XR environments as situated, active, and extended cognitive engagement. However, none of these theories individually captures the complexity of cognitive processes during XR immersion, nor does any dedicated instrument currently exist to measure cognitive extension. In the next section, we present XRCES, a specifically designed instrument for this purpose.

III. SCALE DESIGN

By building on the cognitive theories reviewed in Subsection II-B and, in particular, on extended cognition [25], we identified *perception*, *memory*, *attention*, *embodiment*, *thinking*, *integration*, and *sustainability* as key dimensions describing how XR supports users in visualizing, remembering, focusing, interacting, solving problems, and sustaining cognitive benefits beyond the immediate experience. We directly translated these constructs into seven dimensions along which cognitive function can be extended in XR, as follows:

- D1** *Perceptual Extension* refers to the capacity of an XR system to amplify perception, enabling observation of details, structures, and spatial relationships that would otherwise not be evident. This dimension is grounded in the principles of embodied cognition [26], [27] and extended mind theory [28], according to which external tools may become extensions of the brain's perceptual capacities. In XR, this is reflected in the perceived presence of virtual objects and their spatial plausibility.
- D2** *Memory Extension* refers to the extent in which an XR system supports information storage and retrieval, while reducing the need for traditional memorization via spatial and conceptual encoding. This dimension

is supported by cognitive offloading and distributed cognition [29], [30], according to which external artifacts can assume cognitive functions, e.g., memory related.

- D3** *Attention Extension* reflects the ability of an XR system to guide focus toward relevant elements and filter distracting stimuli. This dimension is grounded in cognitive psychology principles about the limited capacity of attention [31], and is essential for maintaining focus during complex tasks and in multisensory environments.
- D4** *Embodiment Extension* refers to the extent to which XR enhances the user's ability to manipulate virtual objects and/or the environment. It is based on embodiment and motor interaction [26], and involves synchronization of user movement and system feedback, with the benefits of increasing task efficiency and perceived sense of agency.
- D5** *Thinking Extension* measures the extent to which an XR system facilitates construction and manipulation of mental models, thereby supporting thinking processes and decision making. This dimension is theoretically supported by the concepts of cognitive coupling and extended cognition [28], and is linked to classical educational taxonomies [24] that define understanding, application, and analysis as complex cognitive processes, while it directly relates to extended thinking [20].
- D6** *Cognitive Integration Extension* describes the degree to which an XR system becomes an integral part of the user's thinking process, being perceived as an extension of cognition instead of a mere tool. This dimension reflects the 4E cognition principles [27] and human-system integration [28], [29], highlighting the naturalness of the feeling that the user thinks together with the system.
- D7** *Cognitive Sustainability Extension* evaluates the balance between the benefits of cognitive extension provided by an XR system and the risk that the user's performance may become dependent on the system. This dimension is grounded in extended mind theory and studies on cognitive externalization [28], and is relevant for interpreting performance and cognitive safety in XR environments.

Based on these dimensions, we structured XRCES in the form of 18 items assessed on a 5-point Likert scale ranging from 1 (very little) to 5 (very strong); see Table I. We developed the items through an iterative refinement process, starting by identifying cognitive constructs based on theoretical foundations in [26]–[31] and translating them into an initial pool of candidate items, which were iteratively revised and consolidated through consensus in a working group of four researchers with expertise in information technology, computer science, and educational sciences. The resulting instrument underwent an independent review by a fifth researcher with expertise in XR, leading to further refinements in terms of item wording, alignment with the dimensions, and formulation of the corresponding questions. Throughout this process, the working group aimed to eliminate redundancy and balance item coverage across the seven dimensions, resulting in a minimum of two and a maximum of three items per dimension

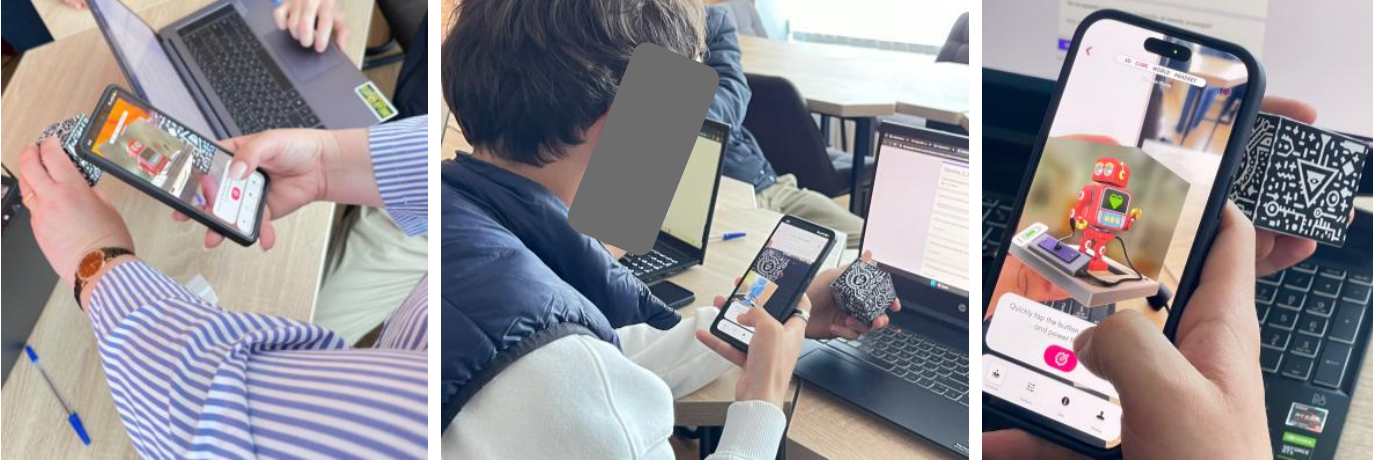


Fig. 1. Photographs of participants using a mobile AR application in our study; see Table II for details on the experimental tasks.

TABLE I
THE EXTENDED REALITY COGNITIVE EXTENSION SCALE (XRCES)

Item	Dim.	Question
Q1	D1	To what extent did you perceive the virtual object as if it were real?
Q2	D1	To what extent did you feel that the virtual object occupied a specific location in the physical space?
Q3	D1	To what extent did the presence of the virtual object become more salient to you than the surrounding physical environment?
Q4	D2	To what extent do you remember the virtual object as a 3D element that you explored, rather than as a 2D image?
Q5	D2	To what extent did you feel that you naturally retained the information provided by the virtual object, without conscious memorization effort?
Q6 [†]	D3	To what extent did you have to exert effort to remain focused on the virtual experience, while ignoring the surrounding physical environment?
Q7 [†]	D3	To what extent did you have to exert effort to follow and understand the information provided through the virtual object?
Q8 [†]	D3	To what extent did you have to exert effort to refocus your attention on the virtual object after interruptions?
Q9	D4	To what extent did you feel that the virtual object responded directly to your actions?
Q10	D4	To what extent did you feel that the responses of the virtual object were smooth and predictable, without appearing artificial?
Q11	D4	To what extent did you feel that you were interacting with the virtual object as if it were real?
Q12	D5	To what extent did you feel that you could solve the task by using visual cues from the virtual environment, without the need for prior mental calculations or deductions?
Q13	D5	To what extent did you feel that the solutions you found were your own, even though you were guided by the application?
Q14	D5	To what extent did you feel that you were able to make decisions more quickly than if you had worked with traditional paper-based materials?
Q15	D6	To what extent did the application clearly show you the steps required to solve the task?
Q16	D6	To what extent did you feel that the application helped you detect and correct errors in real time?
Q17	D7	To what extent did you feel that the application made the task appear much easier than would have been without using the application?
Q18	D7	To what extent did you feel that you learned new information through the virtual object?

[†]Ratings to these question must be reverse-scored.

($M=2.6$, $SD=0.5$). The overall score is computed as follows:

$$XRCES = \frac{1}{7} \sum_{i=1}^7 D_i \quad (1)$$

where each dimension's score is the mean of its corresponding items, e.g., $D_1=(Q1+Q2+Q3)/3$. The final score lies in $[1, 5]$, where 5 indicates maximum perceived cognitive extension; see Table III and Section IV for numerical examples.

IV. STUDY

We administered XRCES in a controlled between-subjects experiment with two groups by varying the duration of exposure to an AR mobile application designed for STEM learning.

A. Participants

Forty-eight participants (30 male and 18 female), aged between 19 and 21 years ($M=19.8$, $SD=0.8$), all university

students representative for target end users of STEM learning, volunteered for the experiment. Participants were randomly assigned to two independent groups of equal size, equivalent in terms of prior digital experience and learning expectations; see Figure 2 for an overview of our participants' demographics.

B. Design

The study was implemented as a between-subjects design with one factor, EXPOSURE, with two levels: *short* (interactions lasted 20 minutes) and *long* (40 minutes).

C. Apparatus and Procedure

The XR environment consisted of a mobile AR application, available through Merge EDU and employing the Merge Cube,¹ which allows exploration of 3D virtual models through

¹Merge EDU Immersive Learning Platform, <https://mergeedu.com>

TABLE II
DESCRIPTION OF THE EXPERIMENTAL TASKS AND THEIR ASSIGNMENT TO GROUPS ON THE EXPOSURE VARIABLE

Task (duration)	Details	Group 1 (short exposure)	Group 2 (long exposure)
Sunlight on the surface (6 min)	Explore the relationship between solar energy, temperature, and living conditions by controlling the amount of energy received by the Earth from the Sun and observing its effects on environmental conditions. The purpose is to support understanding of the relationship between solar energy and the balance of living conditions on Earth.	✓	✓
Solar Robot (7 min)	Observe how the light reaching the solar panel is transformed into electrical energy, which produces the movement of the robot.	✓	✓
Crank Robot (7 min)	Operate a virtual crank and observe how the kinetic energy produced through movement is transformed into electrical energy and subsequently into motion.	✓	✓
Analysis (6 min)	Analyze solar, kinetic, and electrical energy.	—	✓
Comparison (7 min)	Compare the mechanical and solar robots according to energy source, type of energy transformation, energy that powers the robot, final effect, and user role.	—	✓
Cognitive transfer (7 min)	Explain the effects of modifying energy sources: imagine that the Crank Robot is no longer powered by a crank, but by a solar panel similar to the Solar Robot and explain what changes in the system, what the new energy source is, what transformation takes place, and what remains unchanged in the operating mechanism.	—	✓

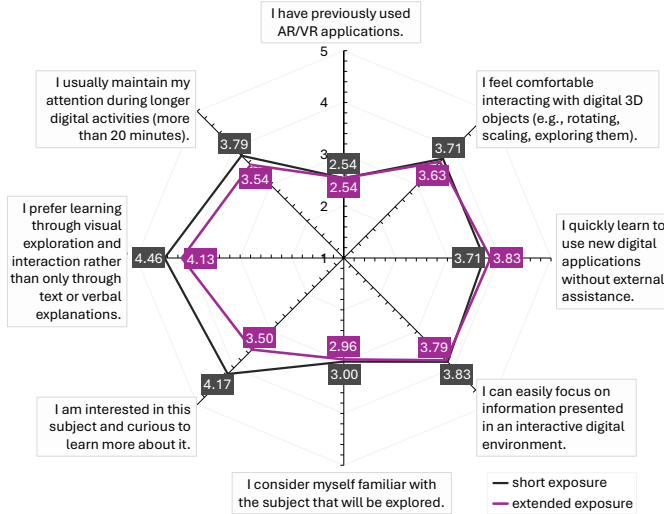


Fig. 2. Participants' demographic details. The two samples, corresponding to *short* and *long* exposure, were equivalent in terms of prior experience with XR, digital interaction skills, attention, and learning preferences.

a smartphone. By manipulating a physical cube, users engage in learning tasks, such as observing sunlight on planetary surfaces and exploring information about a solar-powered robot (Figure 1). The study consisted of four stages: pre-experiment, technical training, intervention, and post-experiment.

The *pre-experimental stage*, aimed at collecting participants' demographics and determine the homogeneity of the two groups, involved the completion of an 8-item questionnaire using a 5-point Likert scale. The items were designed to assess previous experience with XR, perceived comfort in interacting with digital 3D objects, the ability to learn new digital applications quickly, perceived concentration in interactive digital environments, familiarity with and interest in the topic of the proposed tasks, preference for visual-interactive learning, and the ability to maintain attention during digital activities lasting more than 20 minutes. Group equivalence was

confirmed by independent *t*-tests, both overall ($M=3.65$ vs. $M=3.49$, $t_{(46)}=0.753$, $p=.452$, *n.s.*) and across seven of the eight items, indicating no significant pre-existing differences between the two groups ($p>.05$, *n.s.*); see Figure 2.

During the *technical training stage*, participants were instructed on how to use the AR application. They were guided to manipulate the physical cube and observe the virtual objects.

The *intervention stage* involved topics about energy conservation and transfer. Both groups completed a common set of three tasks (Sunlight on the Surface, Solar Robot, and Crank Robot), while the long exposure group continued with three additional tasks (Analysis, Comparison, and Cognitive transfer); see Table II. The tasks were designed to stimulate deeper cognitive processing and maintain engagement.

Lastly, in the *post-experimental stage*, participants filled in the XRCES questionnaire to describe their experience.

D. Results: Comparative Analysis Between Groups

We found a statistically significant effect of EXPOSURE (3.11 vs. 3.87, $t_{(46)}=-5.751$, $p<.001$, with a large effect size $d=-1.66$). Participants in the *long* exposure condition reported 24.4% higher levels of cognitive extension compared to those in the *short* exposure group. Standard deviations were comparable (0.51 and 0.41), and a Levene's test indicated no statistically significant difference in variance between the two groups ($F_{(1)}=2.357$, $p=.132$, *n.s.*). Furthermore, we detected statistically significant effects ($p<.05$) of EXPOSURE on 12 of the 18 individual items (66.7%), confirmed by independent *t*-tests with FDR-corrected *p*-values; see Table III.

Table IV presents the effect of EXPOSURE on each dimension. The largest increases from *short* to *long* exposure were observed for Embodiment Extension D4 (+30.8%), Thinking Extension D5 (+30.7%), and Attention Extension D3 (+27.6%). Memory Extension D2 also increased from 3.62 to 4.06 (+12.2%), but this difference was not statistically significant after the *p*-values adjustment ($p=.051$). All

TABLE III
EFFECTS OF EXPOSURE ON EACH ITEM OF XRCES

Item*	Dimension*	Group 1 (short exposure)	Group 2 (long exposure)	t -test [†]	p [‡] -value	
1	D1	3.21	4.21	-3.719	.002	*
2	D1	3.00	4.04	-3.363	.004	*
3	D1	3.46	3.71	-0.942	.351	
4	D2	3.46	3.83	-1.575	.129	
5	D2	3.79	4.29	-1.933	.071	
6	D3	2.33	3.04	-2.301	.039	*
7	D3	2.46	3.21	-2.659	.021	*
8	D3	2.71	3.33	-2.373	.036	*
9	D4	3.00	4.00	-3.323	.004	*
10	D4	3.17	3.71	-2.005	.070	
11	D4	2.58	3.75	-3.864	.002	*
12	D5	2.88	4.17	-5.061	<.001	*
13	D5	3.21	3.71	-1.836	.082	
14	D5	3.00	4.00	-3.391	.004	*
15	D6	3.25	4.25	-3.762	.002	*
16	D6	3.38	4.00	-2.532	.027	*
17	D7	2.79	3.79	-3.719	.002	*
18	D7	3.54	4.12	-1.966	.071	

*Item correspondence with Table I. [†]Welch's correction applied, with adjusted degrees of freedom for unequal variances. [‡]FDR-corrected p -values.

TABLE IV
EFFECTS OF EXPOSURE ON EACH DIMENSION OF XRCES

Dimension*	Group 1 (short exposure)	Group 2 (long exposure)	t -test [†]	p [‡] -value	
D1 Perceptual Extension	3.22	3.99	-3.767	<.001	*
D2 Memory Extension	3.62	4.06	-2.005	.051	
D3 Attention Extension	2.50	3.19	-2.865	.007	*
D4 Embodiment Extension	2.92	3.82	-4.037	<.001	*
D5 Thinking Extension	3.03	3.96	-4.543	<.001	*
D6 Cogn. Integration Ext.	3.31	4.12	-3.742	<.001	*
D7 Cogn. Sustainability Ext.	3.17	3.96	-3.497	.001	*
Average	3.11	3.87	-5.751	$p<.001$	*

*Dimension correspondence with Table I. [†]Welch's correction applied, with adjusted degrees of freedom for unequal variances. [‡]FDR-corrected p -values.

other dimensions showed statistically significant differences between the *short* and *long* exposure experimental conditions.

E. Results: Correlational Analysis of XRCES dimensions

Table V reports Pearson's r correlation coefficients among the seven XRCES dimensions. The strongest correlations were observed between Thinking Extension D5 and Cognitive Sustainability D7 ($r_{(48)}=.688$), Thinking Extension D5 and Cognitive Integration D6 ($r_{(48)}=.671$), Perceptual Extension D1 and Memory Extension D2 ($r_{(48)}=.630$), and Embodiment Extension D4 and Thinking Extension D5 ($r_{(48)}=.620$), respectively. The weakest associations were found between Perceptual Extension D1 and Attention Extension D3 ($r_{(48)}=.056$), Memory Extension D2 and Attention Extension ($r_{(48)}=-.020$), and Memory Extension D2 and Cognitive Sustainability D6 ($r_{(48)}=.029$). Overall, 43% of the coefficients fall in $[-.200, .600]$, indicating related but distinct constructs and suggesting that XRCES is multidimensional, yet conceptually unified around cognitive

TABLE V
PEARSON CORRELATIONS AMONG THE XRCES DIMENSIONS

Dimension*	D1	D2	D3	D4	D5	D6	D7
D1 Perceptual Extension	—	.630	.056	.557	.578	.330	.558
D2 Memory Extension	.630	—	-.020	.237	.216	.029	.398
D3 Attention Extension	.056	-.020	—	.298	.402	.466	.233
D4 Embodiment Extension	.557	.237	.298	—	.620	.546	.580
D5 Thinking Extension	.578	.216	.402	.620	—	.671	.688
D6 Cogn. Integration Ext.	.330	.029	.466	.546	.671	—	.462
D7 Cogn. Sustainability Ext.	.558	.398	.233	.580	.688	.462	—

*Dimension correspondence with Table I.

extension, whereas another 43% fall in $[-.600, .688]$, showing strong associations. This correlation structure indicates that the XRCES dimensions are related but not redundant, with moderate associations between higher-order constructs.

V. DISCUSSION

The findings from our evaluation offer initial evidence that XRCES captures cognitive extension as a multidimensional experience, complementing what can be measured in terms of usability, workload, and presence with traditional instruments, e.g., SUS [32], UMUX [33], NASA-TLX [21], and PQ [34]. The significant differences between the two groups show that XRCES is sensitive to the duration of interaction. However, our findings should be interpreted with caution because of the relatively small sample ($N=24$ participants per group), whereas larger and more diverse samples (e.g., different levels of XR experience, educational backgrounds, and age groups) are needed to confirm the XRCES structure and its application in various areas, in particular how the dimensions differ across learning domains, educational contexts, and learning goals [13]. Furthermore, the observed differences may reflect not only the longer exposure duration, but also differences in task complexity since participants in the long exposure group completed three additional tasks. Future research should also conduct confirmatory factor analysis, which was less feasible in our study because of the limited sample size, and further examine the low correlations identified in our preliminary analysis, such as between attention and memory extension.

VI. CONCLUSION

We presented XRCES, a multidimensional instrument for assessing perceived cognitive extension in XR environments. In a study involving interactions via a mobile AR application and a tangible interface, we showed that XRCES was sensitive to differences in exposure duration: participants in the long exposure group reported significantly higher levels of cognitive extension, especially in attention, embodiment, reasoning, cognitive integration, and cognitive sustainability. In this context, we propose XRCES as an assessment tool for evaluating how XR enhances cognitive processes.

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