



The impact of visual cues on reducing cognitive load in interactive storybooks for children

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ABSTRACT

Interactive book applications enhance learning by simultaneously conveying visual and verbal information while actively engaging users through interactive elements. This fosters learning through active participation. However, these interactive features can also distract students and increase cognitive load. To address this issue, visually signaling interactive elements on the screen could help guide attention and facilitate the integration of multimodal content. Therefore, this study investigates whether visual signaling of interactive elements can reduce cognitive load and, in turn, improve children's learning performance. A total of 119 children ($M = 9.35$, $SD = 0.684$) were divided into four groups: (1) signaled interactive application, (2) non-signaled interactive application, (3) video, and (4) static-picture control group. The children listened to a science-themed book with various interactive and multimedia elements. Learning outcomes were assessed through a recall test consisting of 16 questions. The ADHD Rating Scale-IV was used to evaluate attentional mechanisms, with assessments completed by the homeroom teachers. Children in the interactive application groups recalled more information compared to children participating in static-picture control group. The children in the video group differed significantly from the control group but not from the interactive application groups. However, children with attentional difficulties tended to perform worse when they watched the multimedia video, or the interactive features were not visually signaled. This negative association was not observed when the interactive features were signaled. The results suggest that using visual signals can be beneficial for children with attentional difficulties by promoting multisensory integration.

Introduction

Advantages of multimedia and interactive elements

Electronic book applications have the potential to promote learning in and outside of the classroom. These applications deliver information with the help of multimedia elements (such as narration, illustrations, animations, etc.) and interactive features (e.g., games, activities, etc.) (Takacs et al., 2015). The impact of interactive elements is still raising many questions. They can be distracting (Parong & Mayer, 2018; Takacs et al., 2015) and may complicate information processing, particularly for individuals with attention difficulties (Bali, Matuz-Budai, et al., 2023). One drawback of these interactive features is that they often require users to search for

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them on the screen, which can increase cognitive load during the learning process (Albus et al., 2021). The aim of this study is to explore ways to reduce the challenges associated with using interactive elements. We propose that one effective method is to clearly indicate the location of these interactive elements on the screen. This approach could help direct children's attention, enabling them to connect and understand the information presented by the interactive elements in relation to the text more effectively (Jamet, 2014).

Advantages of multimedia and interactive elements

Multimedia elements have the potential to deliver information via multiple sensory modalities (Varga, 2014), which makes them particularly applicable for creating an educational environment for effective multimedia learning. The cognitive theory of multimedia learning (Mayer, 2014) posits that learning is more efficient when information is delivered in multiple sensory modalities; e.g., when information is simultaneously explained verbally and visually by a narrated animation (Mayer & Moreno, 1998). Multimedia elements have been the subject of numerous studies which have revealed that these elements have the potential to guide attention and facilitate the comprehension of abstract words, phrases, and complex emotions (Altun, 2018; Herrlinger et al., 2017; Li et al., 2023; Mayer & Anderson, 1992; Takacs & Bus, 2016). They also induce a higher level of engagement and lead to active learning (Mayer & Moreno, 2002). Electronic books can easily deliver these advantages, as they can be combined with a wide variety of multimedia elements.

Interactive features in electronic books can further enhance the benefits of multimedia elements. Interactive features are available in many forms, therefore defining them is challenging (Kucirkova, 2017). Some consider self-paced instructional design interactive (Li et al., 2023), while others use embedded dictionaries or games (Takacs et al., 2015). What they have in common is that they are controlled by the user and aim to involve children in content-congruent activities (Varga, 2014). Content-congruent means that the multimedia elements and interactive features are directly related to the narration and themes presented in the book. These elements are designed to complement and reinforce the information and concepts discussed in the book. In the present study interactive features are considered content-congruent animated figures that become active when children interact with the touchscreen. These specific types of interactive features exert their benefits through playful learning (Hailey et al., 2016; Jusslin et al., 2022; Kangas et al., 2017; Shin et al., 2012) and eliciting content-congruent physical activities, which knowingly improve comprehension and retention (Mavilidi et al., 2016, 2017, 2018; Petrigna et al., 2022; Stapp et al., 2021). Interactive features are also more engaging (Richter & Courage, 2017), and using a device elicits higher levels of motivation and interest (Higgins et al., 2019). However, there are some pitfalls of using interactive features which can result in decreased learning outcome, especially in a diverse population with varying attentional skills.

Pitfalls of using interactive elements

Learning with multimedia and interactivity is a complex process that involves detecting, processing, and integrating information from multiple sources simultaneously (Mayer, 2002). Since we have only a limited amount of cognitive capacity to manage all these parallel processes, the design of electronic books should aim to keep the cognitive load as low as possible to avoid cognitive overload (Ayres & Sweller, 2014). Precise timing is key for successful multimedia learning and reducing the cognitive load (Liu et al., 2022). Synchronization decreases the risk of splitting attention and helps to connect and integrate the perceived pieces of information. This principle is known as the *contiguity principle* and heavily relies on Baddeley's theory of working memory (Baddeley, 1992). The idea is that when the textual and pictorial representations are simultaneously presented there is no need to hold one piece of information in working memory until the other appears. This strategy is expected to reduce the risk of cognitive overload (Mayer & Moreno, 2003). Information is considered synchronized (both in time and content), if an animation begins to move, or a child activates an interactive feature when the corresponding information is spoken.

While contiguity is feasible for automatic multimedia elements, it can be easily violated for interactive features. Multimedia elements are automatic, consequently, with the right timing, the corresponding visual and textual information is presented simultaneously. Interactive features, however, are controlled by the user, therefore, children may use them in a way that is not synchronized with the verbal information. This could mean that children may activate interactive features earlier or even later than the corresponding information is provided. This may explain the controversy around interactive elements. On the one hand, there are studies that found that interactive features enhance general knowledge acquisition and story comprehension (Bali, Csibi, et al., 2023; Bali, Matuz-Budai, et al., 2023; Son et al., 2020; Xu et al., 2021; Zipke, 2017). On the other hand, there are studies suggesting that these features are distracting and, thus, hinder learning (Parish-Morris et al., 2013; Reich et al., 2016; Takacs et al., 2015). If the synchronization between the verbal information and the corresponding interactive feature is violated it may interfere with the integration of information from different modalities. This can increase the risk of dividing attention between the content of the interactive feature and the verbal information leading to higher levels of extraneous cognitive load (Mayer & Moreno, 2003; Moreno & Mayer, 1999; Sweller & Chandler, 1994). Overall, the questions surrounding the use of interactive elements are likely to arise from issues of definition, the diversity of them, and, most importantly, the lack of examination of individual differences among users.

The role of attentional skills

Children with immature executive attention may struggle with distractions and additional cognitive load caused by interactive elements. The maturation of the executive attention network is still ongoing during elementary school years (Anderson et al., 2001; Best et al., 2009; Zelazo & Müller, 2010). Consequently, it can be challenging for children at this age to focus their attention on relevant content when faced with multiple sources of information. According to the *congruency principle* (Mayer & Moreno, 2003), meaningful

learning only occurs if children engage with interactive features at the same time as they listen to the corresponding narration. Immature executive attention, however, favours the bottom-up rather than top-down processes (Petersen & Posner, 2012). As a result, children are more likely to be drawn to interactive features rather than focusing on the primary learning goals, as they find them more interesting and entertaining. This can disrupt the alignment between interactive features and spoken text, leading to divided attention and higher cognitive load (Bali, Matuz-Budai, et al., 2023). Furthermore, these features provide immediate rewards, making the children prone to the hedonic use of interactive features instead of learning (Makransky et al., 2021). This may result in inappropriate processing (and incorrect recall) due to disorganization and lack of integration of information.

In some cases, the location of interactive features is indicated by visual cues, however, in many electronic books, they remain hidden, which can further increase the temporal distance between the spoken text and interactive features. As children must scan the screen for them (instead of paying attention to the content), hidden interactive features can further decrease the processing capacity (Albus et al., 2021). Signaling interactive features with visual cues might be an effective solution to free up some cognitive capacity while children are using electronic book applications. In multimedia learning, signaling is used to highlight key points and indicate the causal chain of information delivered (Mayer, 2014). Signals could be labels, spotlights, arrows, colours, or pointing gestures highlighting relevant words, pictures, or animations. For verbal information, even intonation and pauses can serve as signals (Van Gog, 2014). These signals highlight key terms and relevant information in the learning material making it easier for students to select and organize information (Schneider et al., 2018). Regarding interactive features, signaling presumably makes it easier to achieve temporal congruence between the spoken text and interactive features. In result, it decreases cognitive load and promotes successful learning because signals can potentially direct attention and minimize searching behaviour (Albus et al., 2021). This is supported by an eye-tracking study, which found that participants spent more time fixating on the relevant parts of the screen when signals were used (Jamet, 2014). This suggests that information selection and maintaining attentional focus were easier when signals were present. This leads to better learning performance by facilitating the integration of the spoken text and corresponding interactive features. These advantages may be even more pronounced for those with attentional difficulties, as they already have a tougher time managing interactivity (Bali, Matuz-Budai, et al., 2023). Signaling is widely studied in the context of multimedia elements (Alpizar et al., 2020; Ozcelik et al., 2010; Schneider et al., 2018), however, little is known about whether signaling can prevent cognitive overload and improve learning when interactive features are used. Furthermore, earlier studies did not investigate how signaling affects processing information for those with attentional difficulties.

In our study, signaling was implemented by placing a visual cue (a hand icon) on all interactive elements on the screen. We created a signaled condition, where these icons helped children to identify the location of interactive features, facilitating the alignment between the interactive features and the narrated content. In contrast, we also aimed to test learning in a “non-signaled” version, where we did not include any visual guidance, requiring children to discover the interactive elements on their own. Temporal contiguity was best preserved in the video condition, where the animations automatically appeared at the appropriate time, in synchrony with the narration. In contrast, in the interactive conditions, children themselves decided when to use the interactive features, which might lead to a mismatch between the text and the interactive content. However, signals served as guidance allowing children to connect interactive features more easily with the narrated content, which might help in keeping synchronicity between the narration and the interactive content.

Goal of the study

In the present study, we aimed to investigate whether visual signals such as pointing gestures to indicate interactive features in electronic books can reduce cognitive load without compromising interactivity. While interactivity in electronic books has many advantages, it must be carefully designed, as it can potentially increase cognitive load, especially for individuals with attention difficulties. Presumably signaling interactive features on the screen can be beneficial as they can direct attention and foster the integration of spoken text and interactive features. This, in turn, reduces the risk of interactive elements violating the congruency principle.

Based on this framework, we formed the following hypotheses:

H1: Children exposed to interactive electronic books achieve better learning outcomes than those exposed only to animated figures or static illustrations, as learning through physical activity enhances learning efficiency.

H2: The benefits of interactivity will be moderated by individual differences in attentional control—specifically, children with less mature attentional mechanisms will show reduced learning gains when interactive features are not signaled. This is assumed because children with worse attentional mechanisms are more likely to be distracted, leading to higher levels of cognitive load. In addition, visual signaling of interactive features will eliminate the association between worse attentional control and reduced learning performance. As a result, learning outcomes can improve, irrespective of individual differences in attention. Signaling interactive elements helps to orient attention and organize information more efficiently, thus we propose that signaling supports learning when interactivity is involved.

Methods

Sample

We recruited a total of 119 Hungarian children (63 girls) between the ages of 8 and 11 ($M = 9.35$, $SD = 0.684$) through elementary

schools. All students were typically developing, with no neurological or other disorders, according to their teachers and parents. Participation was voluntary and children received no compensation for their participation. We excluded 11 children as they were identified as outliers based on their recall performance scores (short Q&A). Outliers were excluded if the recall performance scores on the short Q&A were greater than ± 2 absolute deviations from the median (approximately 8.5 % of all the collected data). The children were randomly assigned to four groups: a signaled interactive application group ($N = 29$), a non-signaled interactive application group ($N = 28$), a video group ($N = 34$), and a picture group (as a control) ($N = 28$). The groups were matched for all the study variables (including inattention, hyperactivity-impulsivity, and verbal skills) and age. The gender distribution across groups was unbalanced, therefore, we controlled for this variable later in the analyses. For the descriptive data and exact statistical values, see Table 1.

The study was approved by the Hungarian United Ethical Review Committee for Research in Psychology (reference no. 2023-06) and was carried out following the Declaration of Helsinki. Parents and teachers were informed about the details of the study. Permission of the parents was requested through an informed consent form. All the children verbally agreed to participate.

Study materials

The book

For the book exposure we created a 16-slide interactive presentation in Microsoft PowerPoint. The presentation focused on outer space, which we found to be age-appropriate, interesting, and unfamiliar for the target population. The slides depicted information from the accompanying narration. To create the presentation, we used content-congruent static pictures, two at maximum per slide. We made the presentation interactive by using the trigger function in Microsoft PowerPoint. First, we embedded a static picture and then animated it. With the trigger function we specified that we want the animation to start on click or on touch if they are used with a touchscreen device. These interactive elements in the electronic books were designed to enhance the narration by providing visual representations of the events and information presented in the narration. Tapping on certain objects or characters may trigger animations that correspond to the actions described in the text. For instance, when the children tap on an apple in one of the scenes, it starts moving downward across the screen, visually representing gravity. This interactive feature ties into the story's explanation of gravity, with a reference to the famous legend of Isaac Newton formulating his theory of gravity after an apple fell on his head. Such interactions are directly linked to the educational content, allowing children to engage with and better understand the concepts being presented.

The book application was presented to the children on a touchscreen device. The accompanying narration was recorded and added to the presentation. The narration was played automatically while children used the application. The content of the book was based on science books for children and was written by one of the authors. For an example see Fig. 1.

In the *interactive application groups*, the children could freely use the application, while they listened to the narration. The interactive application allowed children to actively engage with the content by touching the screen, which triggered animations related to the story. These interactions enabled the children to connect directly with the material, activating relevant animations at their own pace. The narration was automatically activated when children moved on to the next slide. In the *signaled interactive application group*, a small hand icon indicated the location of the interactive features, while in the *non-signaled interactive application group* children could

Table 1

Descriptive data regarding age and cognitive variables (inattention, hyperactivity/impulsivity, and verbal skills) separated by groups. The results of the statistical analyses performed to test group differences are also reported.

	Group	N		Statistics
Sex	Picture	28	(20 girls)	$\chi^2(3) = 13.0, p = .004$
	Video	34	(20 girls)	
	Signaled interactive app	28	(7 girls)	
	Non-signaled interactive app	29	(16 girls)	
	Group	Mean	SD	Statistics
Age (years)	Picture	9.39	0.737	$F(3,115) = 0.208, p = .891$
	Video	9.29	0.676	
	Signaled interactive app	9.32	0.67	
	Non-signaled interactive app	9.41	0.682	
ADHD Rating Scale-IV	Inattention	Picture	5.68	$F(3,115) = 0.252, p = .860$
		Video	5.47	
		Signaled interactive app	6.75	
		Non-signaled interactive app	6.24	
	H/I	Picture	3.21	$F(3,115) = 0.097, p = .962$
		Video	3.85	
		Signaled interactive app	3.86	
		Non-signaled interactive app	3.55	
Verbal fluency	Picture	36.3	9.51	$F(3,115) = 0.561, p = .642$
	Video	35.5	9.23	
	Signaled interactive app	38	10	
	Non-signaled interactive app	38.1	9.03	



Fig. 1. A scene from the interactive electronic book on the topic of outer space. This figure depicts a representative scene from an interactive electronic book on the topic of outer space, created in 2023 by the author and the cognitive psychology MA students. In this scene, children could interact with the touchscreen to initiate movement of the elements, illustrating the birth of a star. The interaction was matched to the accompanying audio narration. The first figure is from the signaled, while the second is from the non-signaled version. The small hand icon locates the interactive function.

search for them on the screen without any additional help. For the *video group*, we created a screen recording of the interactive book. In this version, the animations appeared automatically in sync with the corresponding audio content, requiring no active participation from the children. As a result, the children in the video were passive recipients of the visual content, rather than actively interacting with the electronic book themselves. During the video record the first author activated the interactive features, therefore, in the video version children saw automatic animations instead of interactions. In the video group, we presented this video to the children. The *picture group* was identical to the video condition with that one exception that children saw static illustrations instead of animations. We used the same audio record of the narration for all the different versions. The book exposure lasted approximately 10 min in all four groups.

Recall performance

In accordance with earlier studies (see Furenes et al., 2021; Richter & Courage, 2017), we asked the children to answer 16 questions (henceforth named *short Q&A*) related to the content of the book (e.g., “What is at the center of our galaxy?”, “What are stars made of?”) to measure recall performance. Answers were rated on a three-point scale between 0 and 2 points by two independent scorers. Wrong answers were assigned 0 points, correct but incomplete answers were assigned 1 point, and correct answers were assigned 2 points. The children could achieve a maximum of 32 points by answering all 16 questions correctly. The number of achieved points ranged from 2 to 22 ($M = 10.9$; $SD = 4.87$). A total of 10 independent raters scored the responses, and each response was scored by at least two raters. Agreement between raters was tested with interclass correlation (ICC) in R (version 2023.09.1+494 for macOS) using the ‘irr’ package (Gamer et al., 2022). We used a two-way mixed-effects model with consistency of the ratings (Koo & Li, 2016). The mean ICC value was .968 ($p < .001$), indicating high correspondence between the raters. Because of the high correspondence, we averaged the scores given by the raters to determine the final recall performance scores for each child.

Assessments

ADHD Rating Scale-IV

The homeroom teacher (who spends most of the school day with the children) was asked to complete the ADHD Rating Scale-IV (Perczel-Forintos et al., 2005) for each child. We asked teachers, not parents, to evaluate the children because it was important for comparability that children in the same class be assessed by the same adult. In addition, teacher ratings are more reliable and better predictors of a child’s attentional performance than parental ratings are (Tripp et al., 2006). The 18-item questionnaire measures inattention, hyperactivity, and impulsivity between the ages of 5 and 18 years (McGoey et al., 2007) on two subscales: inattention and hyperactivity/impulsivity. Each item is rated on a 4-point Likert scale ranging from 0 (never or rarely) to 3 (very often), which best describes the child’s behavior over the past six months. The questionnaire has excellent psychometric properties; in this study, McDonald’s ω was .955 for the inattention subscale and .942 for the hyperactivity/impulsivity subscale.

Verbal skills

To control for the verbal skills of the children, we used the semantic fluency task (Sehyr et al., 2018; Socher et al., 2019). Children were asked to generate as many exemplars of a given category as they could under a predetermined time limit (one minute for each category). We used three categories, namely, ‘animals’, ‘fruits’, and ‘clothing’. The task lasted three minutes, one minute per category. As an indicator of vocabulary, we calculated the overall number of correct responses across the three categories. Subordinate and superordinate responses were considered correct, while variations in the same item (e.g., plural forms, colour variations) were not counted. The total number of correct responses for the three categories ranged between 14 and 71.

Procedure

The study was conducted in a quiet, spare room at the schools of the children. The children participated individually, and only the

experimenter was present during the book exposure and the data collection. The experimenter established rapport through a small conversation with the child and then explained what would happen during the task. The child was informed that participation was voluntary and that there were no negative consequences of withdrawal from the study. Participation required the verbal consent of the child. Children were also asked if they were familiar with the presented topic. Children who could talk coherently about the topic in two or three sentences were excluded from the data analyses. This criterion did not concern any child.

We used a between-subjects design, meaning that the children were randomly assigned to one of the four experimental groups (signaled interactive app, non-signaled interactive app, video, picture). Members of the interactive application groups were introduced to the story by an interactive book application on an electronic device such a smartphone or a tablet. In these groups, the children could freely explore the application while the story was presented by the read-aloud function. In the video group, the children held a device dedicated to the experiment in their hands and watched the book without interaction. The picture group was identical to the video group except that the story was accompanied by static illustrations instead of animations. Immediately after the exposure, the children answered the short Q&A including 16 questions, then completed the semantic fluency task. The answers of the children were recorded for later analysis. After the short Q&A, we assessed participants' verbal skills. One session lasted approximately 30 min. Only those children who were able to complete this 30-minute session without interruption were included in the study.

Data analysis

Statistical analyses were performed using the 'lme4' (Bates et al., 2015) and 'emmeans' packages in R (version 2023.09.1+494). We tested our predictions using a random intercept linear mixed model (LMM) with two between-subject factors being the format of the electronic book and the sex of the children. Achieved scores on the retention test were included as dependent variables. The scores on the Inattention and Hyperactivity/Impulsivity subscales of the ADHD Rating Scale-IV were entered as continuous predictors. Interactions between the predictors and the book formats were tested. Where significant main effects were found, post-hoc comparisons between groups were conducted. The random factor was the school of the participants. The dataset that includes computed study variables is available on the Open Science Framework: https://osf.io/8cxbf/?view_only=76de00b6427b428bbbf62dc6633e71df.

Results

Our first hypothesis was that interactivity would enhance learning outcomes. As expected, we found a significant main effect of the book format. Members of both the signaled ($M = 11.33$, $SD = 7.45$, $95\%CI = 8.42, 14.2$) and non-signaled interactive application group ($M = 12.28$, $SD = 7.41$, $95\%CI = 9.46, 15.1$) performed significantly better than did those in the picture group ($M = 8$, $SD = 7.53$, $95\%CI = 5.08, 10.92$). The recall performance of the video group ($M = 10.28$, $SD = 8.05$, $95\%CI = 7.48, 13.1$) differed neither from that of the picture group nor from that of the interactive application groups. The signaled and non-signaled interactive application books did not differ from each other. We found no effect of gender on the recall performance.

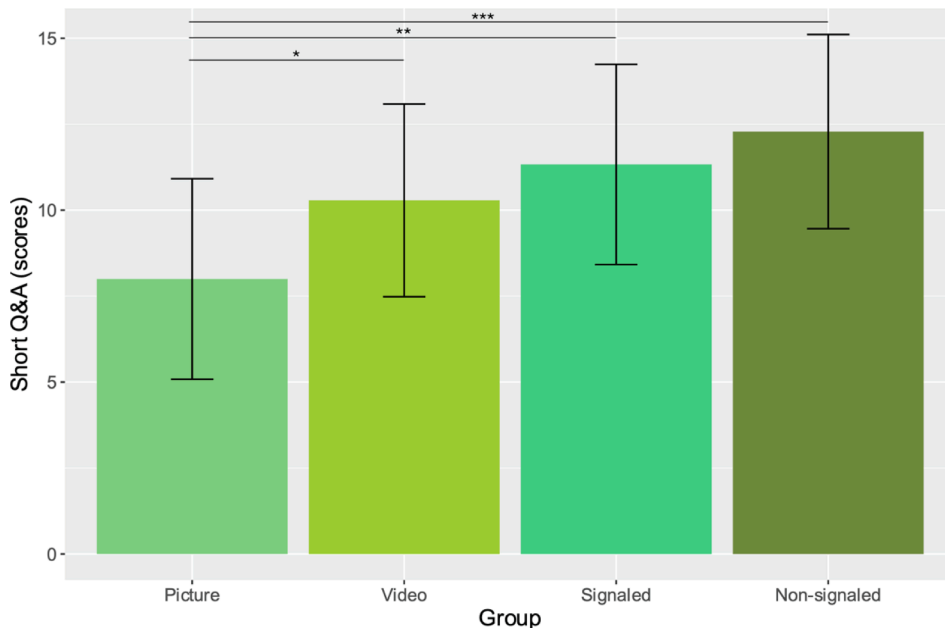


Fig. 2. The students' learning outcomes, represented by the mean scores on the retention test (Short Q&A) separated by groups based on book format. The error bars indicate the 95 % confidence interval. Asterisks indicate statistically significant differences between groups, (* $p < .05$, ** $p < .01$, *** $p < .001$).

In our second hypothesis we proposed that the improvement in children's performance would be influenced by individual differences in attentional mechanisms. We found no significant main effect of inattention; however, the interaction with book format was significant (see Fig. 3). Compared to the picture group ($b = 0.02, p = .929$), in the video ($b = -0.64, p = .002$) and the non-sigaled interactive app group ($b = -0.55, p = .007$), attentional mechanisms showed a negative association with recall performance. Children with higher levels of inattention achieved lower scores on the short Q&A in these two groups. This is in line with our hypothesis as we expected that children with weaker attention skills perform worse when signaling is absent. Therefore, our second hypothesis was supported, as without signaling, the learning performance of the children decreased when interactivity was involved, while their performance was not affected by attentional control when signaling was present ($b = 0.01, p = .952$). Hyperactivity/impulsivity did not affect recall, as we did not find a main effect or interaction. Besides inattention and hyperactivity/impulsivity we also controlled for sex differences in the analysis. We found no significant main effect or interaction related to the sex of the children, indicating that this factor has no association with recall performance in any of the experimental conditions.

The distributions of the scores achieved on the short Q&A are reported in Fig. 2. For the exact statistical values, see Table 2.

Discussion

Empirical contributions

Electronic books with embedded multimedia elements and interactivity are promising tools for improving learning outcomes. They leverage the potential of multimedia learning and the benefits of content-congruent activities through the touch screen (Takacs et al., 2015). While electronic books expand multimedia learning with interactivity which further improves comprehension and retention, interactivity also might be a source of extraneous cognitive load. This is most likely a problem for children who struggle with maintaining attentional focus in the presence of distractors (Bali, Matuz-Budai, et al., 2023). In the present study, our goal was to test whether visual cues, such as pointing gestures, can assist children in maintaining focus and organizing information when an electronic book contains interactivity. Since children typically learn better with multimedia elements and interactivity when the cognitive load is low (Ayres & Sweller, 2014; Sweller & Chandler, 1994), we assumed that using visual cues could help decrease the risk of cognitive overload and making learning more effective.

In line with our first hypothesis children in the interactive application and video groups scored significantly higher on the posttest compared to those in the static picture book condition. There was no significant difference between the interactive groups or between the interactive groups and the video group. Our second hypothesis was also supported by the findings, which showed that attentional

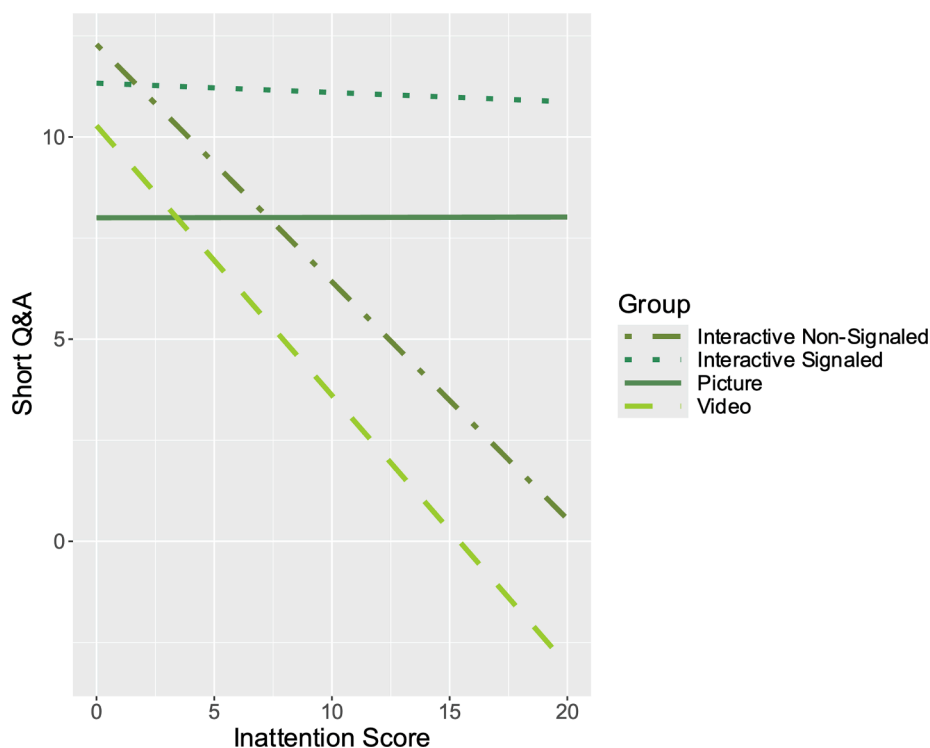


Fig. 3. The relationship between participants' learning outcomes and their inattention scores. The y-axis represents recall performance scores on the Short Q&A, with higher values indicating better performance. The x-axis shows inattention scores, where higher values correspond to greater inattention. Multiple lines are plotted to depict how this relationship varies among different groups.

Table 2

Detailed statistical results of the linear mixed model with pairwise comparisons regarding book format and the main effects and interactions regarding Inattention, Hyperactivity/impulsivity, and sex of the children. Significant interactions are broken down by book format. For significant interactions simple effects are also reported. Significant main effects and interactions are italicized.

Fixed effects				
	b	t	df	p
<i>Picture – Video</i>	−2.28	−2.05	97.8	.043
<i>Picture – Signaled interactive</i>	−3.33	−2.73	97.5	.007
<i>Picture – Non-signaled interactive</i>	−4.29	−3.74	98.1	<.001
<i>Video – Signaled interactive</i>	−1.05	−0.94	97.18	.349
<i>Video – Non-signaled interactive</i>	−2.00	−1.96	97.28	.053
<i>Signaled interactive – Non-signaled interactive</i>	−0.95	−0.84	97.29	.403
<i>Inattention</i>	0.11	0.09	98.6	.929
<i>Hyperactivity/impulsivity</i>	−1.10	−0.72	97.6	.472
<i>Sex</i>	−1.03	−1.12	98.1	.267
<i>Picture-Video * Inattention</i>	−4.07	97.6	−2.38	.020
<i>Picture-Signaled interactive * Inattention</i>	−0.04	98.6	−0.02	.981
<i>Picture-Non-signaled interactive * Inattention</i>	−3.56	98.55	−2.05	.043
<i>Picture-Video * Hyperactivity/impulsivity</i>	−3.34	97.5	1.83	.071
<i>Picture-Signaled interactive * Hyperactivity/impulsivity</i>	1.04	96.9	0.55	.582
<i>Picture-Non-signaled interactive * Hyperactivity/impulsivity</i>	3.73	96.9	1.94	.056
<i>Picture-Video * Sex</i>	2.45	97.8	1.87	.064
<i>Picture-Signaled interactive * Sex</i>	2.20	98.4	1.69	.094
<i>Picture-Non-signaled interactive * Sex</i>	2.32	97.5	1.94	.056
Random effects				
	Variance		SD	
School (Intercept)	7.309		2.704	
Residual	15.49		3.93	
Model fit				
R ²	Marginal		Conditional	
	0.198		0.455	

Model < -mixed(Recall ~ Group * zInattention + zHyperactivity*Group + Group * Sex + (1|School),data = data,control = lmerControl(optimizer = “bobyqa”), REML = TRUE, contrasts = list(Group = contr.treatment(4))).

Key: p-values for fixed effects calculated using Satterthwaites approximations.

processes significantly impact the benefits derived from interactivity. Specifically, children with worse attentional skills scored lower on the posttest in the group that used the non-signaled interactive application. A similar pattern was observed in the video group as well. In contrast, we did not observe this negative association in the signaled interactive condition, where attention scores did not significantly predict performance. These results suggest that while signaling did not enhance overall recall compared to the non-signaled condition, it may have played a compensatory role by narrowing the performance gap between children with high and low attentional skills.

Theoretical contributions

Our results support the idea that interactive features in general, enhance memory encoding and retention (Bali, Csibi, et al., 2023; Bali, Matuz-Budai, et al., 2023; Son et al., 2020; Zipke, 2017). Children remembered the story better when interactivity was involved compared to the version where only static illustrations were included. In contrast to interactive features, recall performance in the video group did not differ significantly from the group with narrated illustrations. Therefore, it seems plausible that adding interactivity has a more pronounced effect on learning compared to the passive reception of embedded animations. These results highlight the advantages of incorporating playfulness (Hainey et al., 2016) and content-congruent activities (Mavilidi et al., 2016, 2017) as opposed to passive learning. It is important to note that both signaled and unmarked interactive elements could achieve the same positive result suggesting that interactive features do not necessarily increase cognitive load and interfere with processing. However, when we consider the individual differences in attentional mechanisms, this result becomes more nuanced.

In line with our hypotheses, and previous literature (Bali, Csibi, et al., 2023) our results suggest that signaling is particularly helpful for children with attentional difficulties. When interactive features were non-signaled, children with higher levels of inattention scored lower on the retention test. In contrast, we found no such association for those in the signaled group. Presumably, this is because, in the absence of visual cues, searching behavior takes up more cognitive capacity and distracts attention potentially by violating the contiguity principle (Albus et al., 2021). Consequently, the likelihood of temporal co-occurrence may decrease as the likelihood of children using interactive features non-synchronously with the corresponding narration increases (Ge et al., 2022; Moreno & Mayer, 1999). Children searching for interactive features on the screen may struggle to effectively organize information and integrate content

delivered through multiple sensory modalities. These processes, however, are fundamental for effective multimedia learning (Mayer, 2002; Mayer & Moreno, 2003). Efficient attentional processes are likely to compensate for the distracting effect of non-signaled interactive elements. This is evidenced by the fact that we found no correlation between attention and learning outcomes when visual cues were used to indicate interactivity on screen.

Interestingly, children with higher levels of inattention also scored lower on the retention task in the video group indicating difficulties with processing even when animated figures were automatically displayed and synchronized with the narration. Multi-sensory integration can be an issue for those with attentional difficulties (Talsma et al., 2010). Thus, even if temporal contiguity is otherwise achieved, performance may still be impaired (Barutchu et al., 2019; Panagiotidi et al., 2017) as children fail to integrate the information coming from different modalities. In the signaled interactive app group, the performance of the children was independent of inattention, suggesting that children with attentional difficulties could successfully integrate visual and verbal information in that condition. This implies that active engagement and promoting information organization may be key elements of multimodal integration. The results also show that the true effect of interactive elements is often hidden when individual differences are not considered, which partly explains the varying results on interactive elements in previous studies. No similar results were found for hyperactivity and impulsivity, which was expected based on earlier literature (Bali, Matuz-Budai, et al., 2023).

Practical implications

Overall, our results show that interactivity, when used correctly, may offer additional value compared to static illustration and even to multimedia elements. In comparison to the achieved scores when static illustrations were presented, interactive animated figures lead to more significant improvements in performance than multimedia elements. Considering the current developmental level of attentional mechanisms, we concluded that those who do not have attentional difficulties perform similarly in a multimedia and interactive environment regardless of using visual cues. For them using non-signaled interactive features will still improve comprehension and learning. However, when it comes to diverse groups of children or helping those with learning difficulties (e.g., children diagnosed with ADHD) signaled interactive features could be the best option for maximum efficiency. In the current study, we defined interactivity as the inclusion of content-congruent animated figures that can be activated by touching the screen, with a maximum of two figures per page. These parameters should be considered when putting our results into practical use.

Limitations

While the results are compelling, it is important to acknowledge some limitations of the study. First, we defined interactivity as using animated figures activated through the touch screen. As a result, our findings may not apply to other types of interactive features. This is important to note because drawing a general conclusion might be misleading due to the great variety of interactive elements (Kucirkova, 2017). This makes it necessary to take the specific type of interactivity under consideration when establishing recommendations. In addition, we only used a limited amount of interactivity – two interactive features per pages. Therefore, the results may not be applicable to more than this number of features. Second, the study was conducted in a laboratory setting, with only the child and the experimenter present in a quiet room, indicating that electronic book applications may be suitable for self-directed learning at home but providing limited insight into their usability in the classroom. Future studies are needed to replicate these results during classroom learning. Finally, although we aimed to involve a diverse range of educational institutions across Hungary (including rural and urban areas), our sample only consisted of typically developing children, limiting the generalizability of our results. To gain a better understanding of their needs, future studies should include children with learning difficulties. Further, future studies should implement eye-tracking data to accurately track visual attention while children learn with the help of electronic books to better understand the role of visual cues.

Conclusion

In summary, when used appropriately, interactive animated figures enhance learning for students aged 8–11. When incorporating them, teachers should consider the current developmental stage of the target group's attentional mechanisms. To maximize effectiveness, we recommend that visual cues, such as pointing gestures, be used to indicate the exact location of interactive features on the screen. Signaling directs visual attention and helps organize information, while interactivity facilitates multisensory integration for students with learning difficulties. These findings should be of great help not only to teachers, but also to developers and parents. The results also underscore the individual needs of students in the digital learning environment provided for them. This underscores the importance of tailoring digital tools to students' specific needs, a step that our findings can help facilitate.

CRedit authorship contribution statement

Cintia Bali: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gergő Várkonyi:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Mónika Szabó:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **András N. Zsidó:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

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Data availability

The dataset that includes computed study variables is available on the Open Science Framework: https://osf.io/8cxbf/?view_only=76de00b6427b428bbb62dc6633e71df.

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