Does Working Memory Capacity Moderate the Effects of Signaling in Multimedia Learning? An Eye Tracking study

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Abstract

The study of multimedia learning involves the presentation of information using both verbal and pictorial forms. One principle that has been shown to enhance learning is the signaling principle. Signaling includes the addition of cues that draw attention to relevant information in the learning material. However, the effects of signaling for learners with different working memory capacities (WMC) remain inconclusive and understudied. This eye-tracking study aimed to fill this research gap by examining whether WMC moderates learning outcomes in the presence of cues, while also exploring attention allocation patterns. Employing a within-subjects design, fifty participants engaged in a multimedia lesson on synaptic transmission, which included color-coded and non-color-coded slides. Each participant was randomly assigned to a group where the order of the cueing conditions was manipulated. Contrary to expectations, the results did not reveal any significant effects of WMC and cueing on learning outcomes. However, cueing did demonstrate significant effects on fixation counts and total fixation duration, indicating that cues effectively directed attention toward the cued elements. Moreover, an order effect was observed, suggesting that the sequence in which cueing conditions were presented influenced fixation behavior. The implications of these findings and future directions are further discussed.

Keywords: Cueing; multimedia learning; eye-tracking; working memory capacity; signaling principle; individual differences

Introduction

The increasing prevalence of e-learning and online platforms in education, particularly resulting from the COVID 19 pandemic, has sparked a growing interest in multimedia learning within educational research (Masalimova, 2022). Multimedia learning encompasses the presentation of information in the form of words (i.e., verbal information) and pictures (i.e., visual information), requiring learners to construct and acquire knowledge through the combination of text and visual elements (Mayer, 2014). Consequently, the presentation of textual (verbal) and pictorial (visual) information in spatial proximity, has proven fruitful in facilitating learners' comprehension, retention, and engagement with learning materials (Mayer, 2014, 2021). The cognitive theory of multimedia learning (CTML) as proposed by Mayer (2014, 2021), is a prominent framework for designing multimedia instructional materials. According to Mayer (2014), meaningful learning encompasses three key cognitive processes: selection of relevant information, organization of the selected information in a coherent mental representation, and lastly, integration of the constructed mental representation with existing knowledge structures (Fiorella & Mayer, 2015). Individual differences in multimedia learning have long been discussed in educational research. The literature suggests that a learner’s level of prior knowledge (Kalyuga et al., 2001; Mayer & Sims, 1994; van Gog, 2021), spatial ability (Moreno & Mayer, 1999), and working memory capacity (WMC) (Daneman & Carpenter, 1980, 1983; Just & Carpenter, 1992) can moderate the process of learning (Antonenko et al., 2020). Research in developmental and experimental psychology has highlighted a close association between working memory, academic progress, and academic performance (Gathercole et al., 2008; Kyndt et al., 2011; Masoura, 2006). Additionally, attentional control has been shown to be positively correlated with academic achievement, as problems in attention can hinder academic performance (Jimmerson et al., 2006). Previous studies have also shown differences in working memory capacity (WMC) to be associated with differences in attentional control (Kane et al., 2001, Unsworth & Robison, 2017). Namely, individuals with lower WMCs are seen to struggle with attention and attending to relevant elements, leading to impediments in their learning process (Fenesi et al 2016, Lusk et al., 2008; Nakamura & Suzuki, 2017; Sanchez & Wiley, 2006; Skuballa et al., 2012; Wiley et. al, 2014). Nonetheless, despite the growth of research and advances in multimedia learning, little attention has been paid to individual differences in WMC when designing instruction (van Gog, 2014, 2021). While the literature on WMC and multimedia learning remain scarce and inconclusive, certain studies have revealed differences in learning outcomes between high and low WMC individuals (see Batka & Peterson, 2005; Doolittle & Altstaedter, 2009; Fenesi et al., 2016; Sanchez & Wiley, 2006; Wiley et al., 2014). Therefore, more attention should be devoted to individual differences in WMC when investigating the effectiveness of multimedia learning designs. Given that the literature suggests a close link between differences in WMC, attentional processes, and academic performance, the primary aim of my study is to investigate whether signaling in multimedia learning can foster learning for individuals with a lower WMC and whether it impacts attention allocation. The signaling (or cueing) principle suggests that incorporating cues in learning materials can direct learners' attention toward relevant information which can foster students' learning (van Gog, 2021). The current study employed cueing techniques in a multimedia learning lesson where fixation behaviors were collected. The study holds significant importance as it aims to address the existing gap in the literature regarding the impact of individual differences in WMC and signaling on multimedia learning and attention allocation. Research in this area can help in cultivating instructional materials that cater to learners of different cognitive abilities, ultimately promoting more equal learning outcomes. Such investigations bear notable implications for instructional design.

WMC and Cognitive Theory of Multimedia Learning

Working memory capacity (WMC) is generally defined as the ability to retain and manipulate multiple items while performing cognitively demanding tasks (Barrett et al., 2004; Engle et al., 1999). Although working memory is inherently limited in its capacity, individuals still exhibit differences in their WMC. Several studies investigating individual differences in WMC have consistently found a positive correlation between WMC and performance on cognitive abilities such as fluid intelligence and attentional control (Conway et al., 2002; Kane et al., 2001). The effective control and allocation of attention are critical factors that impact performance on complex working memory tasks. Previous research focusing on working memory tasks and attentional control, such as cued visual search tasks (Poole & Kane, 2009), has provided evidence supporting a positive association between individual differences in WMC and attentional control. Attention control refers to an individual's capacity to selectively attend to task-relevant information while actively maintaining it in working memory, even in the presence of external or internal distractions (Unsworth & Robison, 2017). The ability to control attention is particularly crucial for learning because it determines which elements learners choose to focus on while disregarding others, thereby influencing their overall learning experience. Given that attentional control is a major component underscoring differences in WMC, low-WMC individuals are more likely to face challenges in selecting information, which could impede the learning process (Lusk et al., 2008). For example, Sanchez and Wiley (2006) conducted an eye-tracking study in which participants' eye movements were tracked as they engaged in a multimedia lesson featuring seductive (irrelevant) images. The study aimed to discern distinctions in attention allocation and comprehension performance between high and low WMC individuals. Findings revealed that low-WMC individuals exhibited more attention allocation toward seductive illustrations, which subsequently lead to lower performance on comprehension tests in comparison to high-WMC participants. Differences in WMC have recently gained attention as important factors within the CTML especially when studying and designing multimedia instructional materials (Antonenko et al., 2020; Wiley et al., 2014). According to the CTML, successful multimedia learning requires learners to select, organize and integrate relevant information (Mayer, 2009). In essence, CTML posits that learners actively select, organize, and integrate information. Additionally, it recognizes the limited capacity of learners to process information simultaneously (Cavanagh & Kiersch, 2022). The limited literature on multimedia learning principles and individual differences in WMC has thus far shown that poorly designed learning materials have a particularly adverse impact on low WMC learners (see Batka & Peterson, 2005; Fenesi et. al, 2016; Lehman et al., 2007; Rey, 2012, 2014; Sanchez & Wiley, 2006; van Gog, 2021). To investigate the relationship between individual differences in WMC and the split-attention effect, Fenesi et. al (2016) conducted two experiments wherein university students were exposed to two different learning conditions: one presenting multimodal information in an integrated manner (complementary) and the other with spatially segregated information (split-attention). When exposed to the split attention condition, individuals with lower WMC performed more poorly on learning compared to high WMC individuals. However, in the complementary condition, where split-attention components were absent, low WMC individuals had better learning outcomes compared to their performance in the split-attention condition. The results from both experiments show that multimedia learning design can either benefit or negatively impact those with lower WMC, depending on how the information relevant to the learning objective is presented.

Given low WMC learners are more likely to struggle with attention allocation in multimedia learning contexts, such individuals often encounter challenges attending to the relevant elements of the learning material. In light of the CTML, one of the multimedia design principles that could be particularly crucial for the first step in learning is the signaling principle (Mayer, 2014; van Gog, 2021).

The signaling principle

The signaling (or cueing) principle in multimedia learning is grounded in the finding that individuals learn more effectively from multimedia content when cues are added to guide attention to relevant elements of the learning material (Alpizar et al., 2020; Richter et al., 2016; Schneider et al., 2018). According to the CTML, the primary phase of effective learning requires learners to attend to and select relevant elements to proceed to the organization and integration of information (de Koning et al., 2009; Mayer, 2009; Johnson et al., 2014). Generally speaking, cues can be incorporated into the multimedia learning material in various forms including pictures, text, or a combination of both. Text-based cues include capitalization, underlining, bolding, and color coding, whereas picture-based cues include elements such as arrows or labels that are considered extrinsic as they are not inherent to the picture (Boucheix & Lowe, 2010; Lin & Atkinson, 2011, van Gog, 2014). Cueing in multimedia learning has been seen to be effective in aiding bottom-up processing (Hu & Zhang, 2021; Kriz & Hegarty, 2007) and this can be explained by perceptual theory which posits that stimuli with distinct characteristics, such as color, play a role in facilitating visual search (Itti & Koch, 2000; Treisman & Gelade, 1980) and can enhance the saliency of the stimulus material (Hillstrom and Chai, 2006; Jamet et al., 2008). Consequently, low WMC individuals can benefit more from learning in attention-guiding environments compared to those with higher WMC. Wherein bottom-up guidance can mitigate the impact of WMC on selective attention (Shipstead et al., 2012). Color coding has been seen to have facilitative effects on learning outcomes in multimedia learning contexts (de Koning et al., 2007; Jamet, 2014; Ozcelik et al., 2009; Richter et al., 2016), especially in selecting and attending to the key elements of the learning material (Skuballa et al., 2012). A study by Jamet and colleagues

(2008) investigated the impact of color coding in a multimedia lesson consisting of both texts and pictures. Results of this study showed that participants in the cued condition outperformed participants in the non-cued condition, both on the comprehension and transfer tests. This can be partly attributed to a reduction in visual search which ultimately allows for attentional resources to be directed toward the cued elements. Despite the existing literature on signaling in multimedia learning, there remains a research gap in studies examining the influence of cueing on learning outcomes for individuals with different WMCs. Studies investigating this topic, have also yielded inconsistent findings where no interaction between cueing, WMC, and learning was revealed (e.g., Nakamura & Suzuki, 2017). In light of CTML, the meta-analysis by Alpizar and colleagues (2020) indicates that the use of cues can be effective in directing learners' attention to the relevant elements of the learning material. Signaling in this case facilitates the cognitive process of selection and enables them to expand their limited cognitive and attentional resources on elements relevant to the learning objective. This can be particularly beneficial to individuals with limited attentional control who are most likely to struggle with the selection process. Despite the studies examining the effects of cueing on learning in multimedia instructional environments, there is a scarcity of methodological and systematic research investigating the effects of cueing on individual differences in WMC as well as attention allocation (van Gog, 2014, 2021).

Attention and signaling

While prior research has indicated the potential of signaling in facilitating attention guidance and improving learning outcomes (de Koning et al., 2007; Jamet et al., 2008; Ozcelik et al., 2010), the available literature on this topic remains limited and inconclusive. Nevertheless, the aforementioned studies examining attention allocation, differences in WMC, and multimedia learning suggest that the use of cueing can be particularly advantageous for low WMC individuals, who often encounter challenges in the selection process (Fenesi et. al, 2016; Lusk et al., 2008; Sanchez & Wiley, 2006). Although the CTML provides a foundation for deriving various principles for multimedia design (Mayer, 2014), there remain inherent challenges associated with measuring and quantifying cognitive processes, including the allocation of attention to multimedia learning elements (Alemdag & Cagiltay, 2018). For such reasons, eye-tracking technology has been more widely used in educational research specifically when investigating multimedia learning principles concerned with attention (for example, seductive details, signaling, and split-attention; see Jamet 2014; Mutlu-Bayraktar, 2022; Ozcelik et al., 2010; Rey, 2014). The eye-tracking method allows us to uncover where individuals attend, for how long, and in what order which gives some indication of what they are cognitively processing (Just & Carpenter, 1980). In relevance to the signaling principle, eye-tracking measures can provide insights into how certain cues affect selective visual attention (Boucheix et al., 2013; Boucheix & Lowe, 2011; Jamet, 2014; Ozcelik et al., 2010; Wang et al., 2020). Several eye-tracking studies investigating the signaling effect on attention allocation have shown that in some cases, the use of cues can reduce visual search which ultimately facilitates attention allocation (Jamet, 2014; Jarodzka et al., 2013; Ozcelik et al., 2010; Scheiter & Eitel, 2015, Xie et al., 2019). This can be deduced from longer fixation durations (i.e., how long) and higher fixation counts (i.e., how often) individuals look at the cued information. These metrics serve as valuable indicators of the level of attention and cognitive engagement individuals exhibit during the learning process (Holmqvist et al., 2011; Just & Carpenter, 1980; Ozcelik et al., 2009; Rayner, 1998; Xie et al., 2019).

A study by Jamet (2014) investigating the impact of textual and pictorial cueing- specifically color change- on total fixation times, revealed that the fixation duration on the relevant information in the cued conditions was significantly longer than in the non-cued conditions. These results align with the notion that visual signals have an influence on the selection process in multimedia learning environments (Johnson et al., 2014). Nonetheless, there are still inconsistencies in the literature. For example, Hu and Zhang (2021) conducted an eye-tracking study investigating the effects of cue labeling, particularly text size and color coding, on a multimedia learning lesson consisting of static textual and pictorial information. Contrary to expectations, the study found that fixation counts, and fixation durations were higher and longer in non-cued conditions and with larger text labels. The results from the studies mentioned indicate that integrating more eye-tracking data to assess attention allocation in the presence of cues, provides valuable insights into learners' visual attention and the cognitive processes involved in the processing of the learning material (Li et al., 2019; Liu et al., 201, van Gog & Scheiter, 2010).

The present study

To recapitulate, the use of signaling in multimedia learning has been found to have positive effects on learning performance. Several studies have demonstrated that when cues are incorporated into a multimedia learning lesson, there is an improvement in comprehension, retention, and attention allocation. However, as mentioned previously, due to differences in learning, these results are not uniform across all individuals. One factor that has been suggested to influence learning outcomes is WMC. Although there is limited research on the interaction between WMC and the effectiveness of signaling, it has been observed that low-WMC individuals tend to derive a more noticeable benefit in learning in the presence of cues compared to high-WMC individuals (Batka & Peterson, 2005; Fenesi et. al, 2016; Jamet et al., 2008). Nonetheless, research on signaling and individual differences in WMC is not only limited but has also yielded inconsistent findings. Building upon the aforementioned points and research gap, this paper aims to investigate two key aspects. Firstly, it aims to examine whether WMC is predictive of learning outcomes in the cued and non-cued conditions. Secondly, it seeks to explore whether fixation behaviors change in each condition. Consequently, I hypothesized the following:

1) In order to examine whether WMC has a moderating effect on learning outcomes in the presence or absence of cues, I expected WMC to exhibit a more pronounced impact on learning for participants with lower WMC in the cued than in the non-cued conditions. This would be reflected by an improved performance on the comprehension test. The investigation builds upon the assumption and findings from previous studies suggesting that lower WMC individuals perform better when cues are present (de Koning et al., 2007; Jamet, 2014; Ozcelik et al., 2009; Richter et al., 2016; van Gog, 2014, 2021). The hypothesis is grounded in the Selection, Organization, and Integration (SOI) model of the CTML, whereby meaningful learning is first carried out through the selection of elements pertinent to the learning objective (Mayer, 2014).

2) In order to explore potential differences in attention allocation between the cued and non-cued conditions, I hypothesized participants in the cued conditions to exhibit longer fixation durations and higher fixation counts. This prediction is grounded in the attention-guiding effect of cueing, which facilitates visual selection by directing individuals' attention to the signaled elements in the learning material (Alpizar et al, 2020; Hu & Zhang, 2021; Shipstead, 2012; Skuballa et al., 2012).

Methods

Participants

A total of 50 university students (29 female, 21 male) partook in this study on a voluntary basis whose average age was 25.64 years (*SD* = 2.15). All participants had normal or corrected-to-normal vision and basic English proficiency. Undergraduate psychology students were given one course credit upon participation. This experiment was conducted in accordance with the ethical guidelines stipulated by the Ethics Review Board of the Faculty of Social and Behavioral Sciences of the university where this study was conducted. Using a counterbalanced within-subjects design, both groups of participants (n = 25 each) were exposed to cueing and non-cueing conditions within the same multimedia learning module. The only distinction between the groups was the order in which these conditions were presented. In the first group, participants received the cueing condition followed by the non-cueing condition, while the second group received the reverse order. This design ensured that any potential sequence effects were evenly distributed across the two groups, enabling a comprehensive examination of the impact of cueing on learning outcomes.

Materials and apparatus

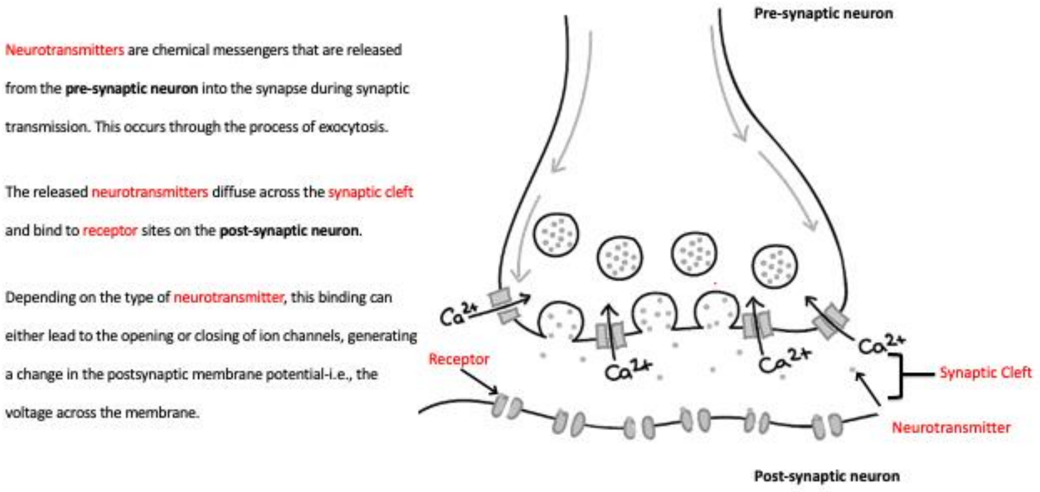
Eye tracking device

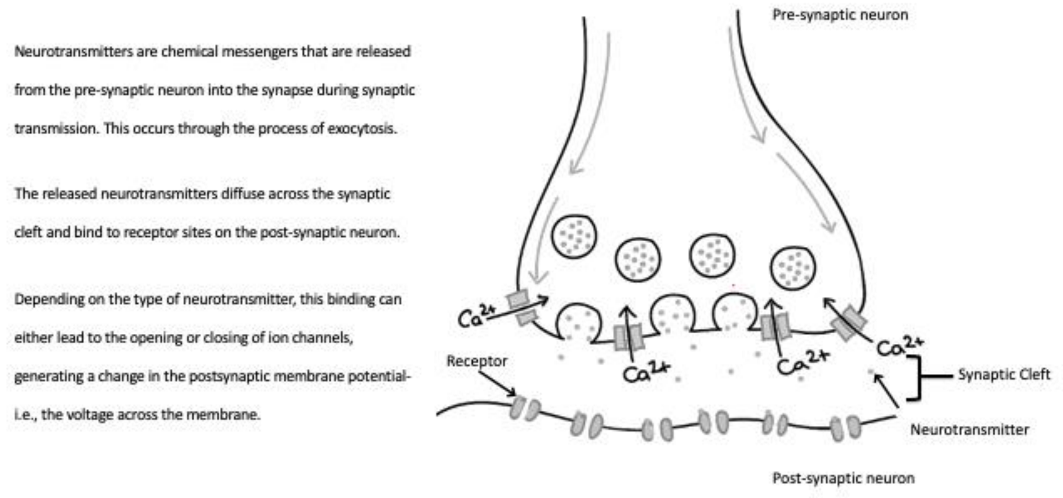
Fixation duration and fixation counts were collected using a screen-based Tobii Pro Spectrum eye tracker with a sampling rate of 300 Hz and a screen resolution of 1920 x 1080 Hz. The fixation filter employed was Tobii I-VT Fixation. The eye tracking data, which involved tracking both eyes, was recorded, and analyzed using the Tobii Pro Lab program version 1.194.41215 (x64). To ensure accuracy, a timed calibration process was performed with 5 calibration target points, which resulted in a validation accuracy (root mean square) of 0.51 degrees (SD= 0.20; Min=0.22, Max=1.58) and precision (root mean square) of 0.11 degrees (SD= 0.10, Min=0.03, Max= 0.56).

Multimedia instructional material

The study involved the presentation of an instructional slideshow comprising eight slides explaining the biochemical processes of synaptic transmission. Each slide included a combination of expository text and a labeled illustration. All slides in the module utilized the same font type and size (Calibri, 19) and were presented in English. The text per slide contained a word count ranging from 73 to 111 and the picture contained 2 to 5 words. The number of cued words in text varied from 2 to 11 and in the corresponding pictures, the cues ranged from 2 to 5. It must be noted that the same cued words in the text were repeated more than once than in pictures. The first two slides were solely introductory, while the remaining six slides included the cueing conditions. Two versions of the module were administered: In group 1, the cueing conditions were presented in the first set of the three slides, followed by non-cueing in the last three slides. For group 2 the order of the conditions was reversed. The cueing condition was manipulated as the only within-subjects factor. The color red and bolding were used to highlight relevant words in both the text and picture on each slide (see Figure 1). The presentation was self-paced.

Figure 1:
An example of the cued (top) and non-cued (bottom) version of Slide 5 in the multimedia lesson





Prior knowledge questionnaire

To gauge participants' pre-existing understanding of synaptic transmission, a prior knowledge questionnaire was administered. The questionnaire comprised five Yes/No items designed to evaluate participants' familiarity with key concepts related to synaptic transmission. For instance, one of the items assessed participants' familiarity with the terms "pre-synaptic" and "post-synaptic". Each correct response received one point, yielding a maximum possible score of 5. The data from the questionnaire were managed using the Qualtrics XM software.

Operation Span Task

The automated operation span task (AOspan), developed by Millisecond Software, was used as a means of measuring participants' WMC. The AOSpan has an internal consistency with a Cronbach's Alpha of 0.78 and test–retest reliability value of α= 0.83 (Unsworth et al., 2005). The mouse-driven task was run on Inquisit Player 6 presented on a computer screen. The AOspan task was divided into three sections within the same session. Initially, participants engaged in a practice session where they were asked to recall letters in the order they were presented on the screen. Following that, a section involving operational math problems (e.g. (8*3) + 4=?) was introduced. The final section combined the two preceding sessions requiring participants to simultaneously complete both the letter recall and the math problem. The task consisted of a practice session and a subsequent test session including 15 test trials. The program calculated and reported the AOspan score which ranged from 0 to 75. For each participant, the AOspan score was determined using the absolute OSpan scoring method which involved summing the number of perfectly recalled sets.

Comprehension test

A comprehension test consisting of 8 multiple-choice questions, each with 4 possible answers, was administered to assess learning outcomes. 1 point was given to each correct answer. The first 4 questions corresponded with concepts discussed in the first half of the presentation whereas the second corresponded to concepts discussed in the second half of the presentation. Therefore, each participant was tested on their knowledge of the cued and non-cued slides. The test was presented using Qualtrics XM software. The following is an example of one of the questions:

1. **Which of the following is the most accurate statement about the role of calcium ions in synaptic transmission?**

    a. Calcium ions play a role in both presynaptic and postsynaptic signaling, regulating the release of neurotransmitters, and contributing to the depolarization of the postsynaptic membrane.

    b. Calcium ions directly bind to the neurotransmitters and facilitate their release into the synaptic cleft.

    c. Calcium ions cause the synaptic vesicles to merge with the axon terminal membrane, leading to the release of neurotransmitters into the synaptic cleft.

d. Calcium ions are not directly involved in synaptic transmission, but they help to maintain the membrane potential of the neuron.

Procedure

The experiment was conducted in a single session, where each participant was tested individually. Upon arrival, participants were provided with an information letter and an informed consent letter adhering to the Ethics Review Board of the Faculty of Social and Behavioral Sciences, which they were required to read and sign. The experiment involved the completion of four tasks. Firstly, participants performed the AOspan task, followed by the prior knowledge questionnaire on the laptop. Upon completion, they proceeded to the eye tracker setup which was conducted on a desktop computer equipped with the Tobii eye tracker. Each participant received thorough instructions on the eye tracking procedure and multimedia learning task and was randomly assigned to either group 1 or group 2. To ensure consistent positioning, participants were seated in the center and in front of the eye tracker at approximately 57-58 cm from the monitor using a forehead and chinrest for stabilization. Prior to engaging with the multimedia material on synaptic transmission, participants underwent an eye-tracking calibration process using 5 target points, The presentation was self-paced, and participants could only proceed forward with the presentation. After the multimedia lesson, participants were asked to complete the comprehension test on the laptop.

Statistical analysis and design

JASP software 0.17.1 (Intel) and IBM SPSS Statistics (version 28.0.1.1) were used to carry out the data analysis. The design incorporated multiple measures, including WMC scores, prior knowledge test scores, comprehension test scores, fixation counts, and total fixation durations. An alpha level of .05 was used for all statistical tests. As a measure of effect size eta squared ($\eta 2$) was reported, with $\eta 2 = 0.01$, $\eta 2 = 0.06$, and $\eta 2 = 0.14$ representing small, medium, and large effects, respectively (Cohen, 1988).

WMC and learning measures

Data from the prior knowledge and comprehension tests were collected using the Qualtrics XM software (www.Qualtrics.com). WMC scores were calculated by the AOspan program. To examine the moderating effect of WMC on learning performance in the presence of cueing (i.e., hypothesis 1), a linear regression analysis was carried out. By exploring the interplay between WMC and cueing, this study sought to gain insights into how these factors jointly influence learning performance.

Eye tracking measures

Eye tracking data was collected and analyzed using the Tobii Pro Lab software and then exported to Microsoft Excel where percentages of total fixation durations and fixation counts on the designated areas of interest (AoI) in the text and picture were computed. Figure 2 and Figure 3 illustrate an example of the assigned AoI's for slide 5 in each of the cued and non-cued versions respectively. The percentages were calculated by taking the sum of fixation duration (or fixation count) on all AoI's in the text and picture divided by the fixation duration (or fixation count) for the entire slide. Subsequently, for each participant, the fixation duration (or fixation count) for the three cued slides was averaged as was done for the three non-cued slides. Two separate two-way analysis of variance (ANOVA) models were conducted to examine the effects of cueing and order on fixation counts and total fixation durations. Cueing was considered the within-subjects factor, representing the presence or absence of visual cues, while order was the between-subjects factor, representing the sequence in which participants were exposed to cued and non-cued materials. Fixation counts and total fixation durations served as the dependent variables in these analyses.

Figure 2:

AoIs on cued elements (in text and picture) in Slide 5

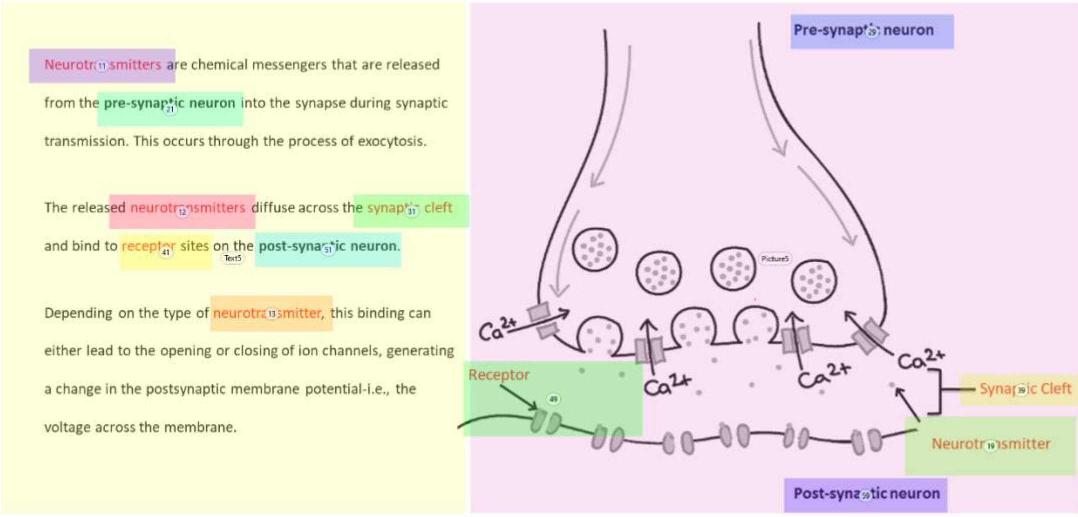
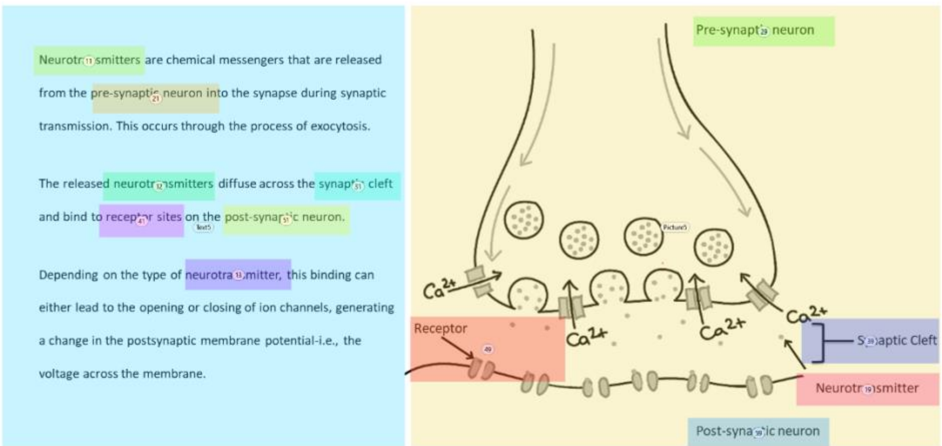


Figure 3:

AoIs on non-cued elements (in text and picture) of Slide 5



Results

WMC and learning performance

To examine the moderating effect of working memory capacity (WMC) on learning outcomes in the presence and absence of cueing, a linear regression analysis was conducted. Prior to analysis, the assumptions of linear regression were assessed and visually inspected. A scatter plot depicting standardized residuals against predicted values indicated no discernible curvature, suggesting linearity. Additionally, the equal spread of standardized residuals across different predicted values indicated the presence of homoscedasticity. The independence of residuals was confirmed by a Durbin-Watson statistic of 1.86, and the associated p-value (> .05) provided no evidence of autocorrelation. Furthermore, the assessment of multicollinearity revealed no substantial concerns, as tolerance and variance inflation factor (VIF) values were greater than 0.1. Working memory capacity (WMC) was treated as a numeric continuous predictor variable, while cueing was treated as a dummy variable.

Table 1:

Means (*M*) and standard deviations (*SD*) of prior knowledge, learning outcomes and WMC for all participants across cueing and non-cueing conditions.

	All	
	M	*SD*
Prior knowledge (0-5)	4.18	1.14

Learning outcomes		
Cued slides (0-4)	2.60	1.20
Non-cued slides (0-4)	2.46	1.18
WMC Score	44.98	14.81

The linear regression models failed to yield statistically significant results ($R^2 = 0.004$, $F(3, 96) = 0.143$, $p = .934$). In reference to Table 2, the main effect of cueing on learning scores was not significant. Similarly, there was no significant effect of WMC on learning scores nor a significant interaction between WMC and cueing. These findings suggest that the hypothesized moderating effect of WMC on learning outcomes, specifically in relation to cueing effects, was not supported by the data.

Table 2:

Regression Analysis Summary with learning as the dependent variable and cueing and WMC as the independent variables

Predictor	*b*	*SE*	*t*	*p*
Intercept	2.61	0.55	4.77	<.001
WMC	-0.003	0.01	-0.30	.770
Cueing	-0.03	0.76	-0.04	.967
WMC * Cueing	0.004	0.02	0.23	.816

Note. b represents unstandardized regression weights

Eye tracking measurements

Two two-way analysis of variance (ANOVA) were conducted to examine the effects of cueing as a within-subject factor (i.e., cueing versus no cueing) and order as between-subjects variable (i.e., first cueing then no-cueing versus no-cueing then cueing) with fixation count and total fixation duration as dependent variables, respectively. The assumption of homogeneity of variances was met for both fixation duration and fixation count as indicated by Levene's test with p-values greater than .05. Descriptive statistics presented in Table 3 illustrate the mean values and standard deviations for both cueing and order.

Table 3:

Means (M) and standard deviations (SD) of total fixation durations on the designated AoI's in both cued (C) and non-cued (NC) conditions, including orders 1 and 2.

		Fixation duration		Fixation count	
Condition	Order	*M*	*SD*	*M*	*SD*
C	1 (C-NC)	78.96	14.90	79.28	14.40
	2 (NC-C)	60.01	22.25	60.50	21.79
NC	1 (C-NC)	50.37	17.91	51.55	17.91
	2 (NC-C)	66.79	21.52	64.96	21.52

The ANOVAs revealed that cueing had a significant effect on fixation duration (F(1,48)= 19.448, η2=.288, p<.001) which means that participants tended to look longer at the AoIs in the cued condition compared to the non-cued condition. No significant effect of order was revealed (F(1,48)= .323, η2= .007, p=.527), indicating that regardless of the cueing condition, there was no effect of the order on overall fixation duration. However, a significant interaction effect between cueing and order was observed ($F(1,48) = 37.215$, $\eta 2 = .437$, $p < .001$). This interaction effect was followed up by Bonferroni post hoc comparisons, which revealed that cueing only led to higher fixation durations on the AoI's only when participants started with the cueing condition followed by the non-cueing condition ($p < .001$), but this was not the case when participants were subjected to the non-cueing condition first. In fact, when presented with the non-cueing slides first, the participants displayed somewhat higher fixation durations on the non-cued AoI's compared to the fixation duration on the AoI's for the cued slides, even though this difference did not reach statistical significance ($p = .238$).

The second two-way ANOVA, with fixation count as a dependent variable, also showed a significant effect of cueing on fixation count ($F(1,48) = 15.84$, $\eta 2 = .248$, $p < .001$) indicating that participants tended to look more often on the cued AoIs than non-cued. Moreover, order did not show a significant effect on fixation counts ($F(1,48) = .064$, $\eta 2 = .001$, $p = .801$) which once again indicates that regardless of the cueing condition, order did not have an effect on fixation counts. However, a significant interaction between cueing and order was revealed ($F(1,48) = 41.20$, $\eta 2 = .462$, $p < .001$). In order to further explore the direction of this interaction effect, a Bonferroni post-hoc test was carried out. The results once again indicate that fixation counts were higher on the cued AoI's than the non-cued ones, especially when participants were subjected to the cued slides at the beginning of the multimedia lesson. Nonetheless, despite this pattern, the difference between fixation counts across both conditions did not have a significant effect ($p = .091$).

Discussion

The present study aimed at investigating whether WMC has a moderating effect on learning in the presence of cueing (specifically color coding, and bolding) while also looking into whether differences in attention allocation can be discerned when cues are used in a multimedia learning context consisting of static texts and diagrams. It has been established that low WMC individuals primarily struggle with attentional processes (Kane et al., 2001; Friso-van den Bos & van de Weijer-Bergsma, 2020; Rosen & Engle, 1997) as well as selection processes (see Fenesi et al 2016; Lusk et al., 2008; Sanchez & Wiley, 2006; Skuballa et al., 2012). Moreover, cueing in multimedia learning has proven effective in guiding learners' attention to information pertinent to the learning objective (Jamet et al., 2008; Skuballa et al., 2012, Tabbers et al., 2004). Based on these studies, I hypothesized that low WMC individuals would demonstrate better learning outcomes in cueing conditions compared to non-cueing conditions. Furthermore, evidence from eye tracking studies shows that individuals display longer fixation durations and higher fixation counts on cued elements in multimedia instructional designs, suggesting the potential for cueing to aid selective attention (Alpizar et al., 2020; Jamet, 2014; de Koning et al., 2007; Ozcelik et al., 2009; Richter et al., 2016). Consequently, for my second hypothesis, I predicted that participants would exhibit longer fixation durations and higher fixation counts on the cued elements in the multimedia lesson compared to the non-cued elements.

Effects of WMC on learning outcomes

Contrary to the initial hypothesis and previous research (Fenesi et al., 2016; Nakamura & Suzuki, 2017; Sanchez & Wiley, 2006; Shipstead et al., 2012; Wiley et al., 2014), the linear regression results did not yield any significant effects of cueing, WMC, or their interaction on learning outcomes. These findings indicate that WMC did not impact learning outcomes in cueing conditions. While these results are partly contradictory to findings from previous research, there are distinctions between this study and the few studies that have examined the effects of signaling on individuals with different WMCs. For instance, to investigate the effect of signaling and WMC on learning, Nakamura and Suzuki (2017) conducted a study using a system-paced narrated multimedia lesson consisting of static illustrations and text explaining human memory. Two versions of the multimedia lesson were presented: cued and non-cued. The narrated sections in the cued version were highlighted in red. Those with a higher WMC performed better than low WMC individuals with a minor effect of signaling. It is important to note that their study differed from this study in terms of experimental design. Unlike their narration-based approach to the multimedia learning lesson, narration was absent in my study and the lesson was self-paced rather than system-paced. According to Mayer (2014), the use of narration in multimedia learning can facilitate comprehension, which could explain why their study yielded a significant effect on learning performance. Furthermore, the aforementioned study employed a more comprehensive exam with 17 questions comprising MCQs, open-ended questions, and diagram labeling tasks. In comparison, my study employed a less comprehensive test with only 8 questions which were multiple-choice questions. This disparity in exam format could also contribute to inconsistent findings. Another plausible explanation for this study's lack of significant results could be credited to the effective design of the multimedia lesson wherein differences in WMC did not substantially influence performance. Consequently, participants may have performed well regardless of their WMC.

Attention allocation and cueing

This study demonstrated a significant impact of cueing on fixation behavior, effectively employing color coding to direct participants' attention toward the cued elements. These findings are consistent with both my second hypothesis and prior research (de Koning et al., 2007; Jamet et al., 2008; Jamet, 2014; Ozcelik et al., 2010), supporting the notion of cueing as a facilitative mechanism for guiding learners' attention. The rationale behind this alignment lies in the shared similarities between this study and previous ones. As I mentioned in the introduction section, color coding and bolding have been shown to display a high level of saliency (Itti & Koch, 2000; Treisman & Gelade, 1980), as well as exhibit facilitative effects in directing attention towards cued elements (Alpizar et al., 2020; Jamet et al., 2008; Schneider et al., 2018; Skuballa et al., 2012). However, it is important to note that this effect was predominantly observed during the first half of the experiment when the cueing condition was presented first. Being the first study in the literature to employ a within-subjects design, these findings can elucidate why previous studies, which considered cueing as a between-subjects factor, did not consistently find an impact on attention, or explain the inconsistent outcomes.

Limitations

In the present study, cueing was found to effectively direct individuals to the signaled elements of the multimedia lesson. However, WMC did not have a significant impact on learning in the cueing conditions. The inconsistency in findings could stem from potential limitations this study holds. One possible explanation for the inconsistent results regarding the first hypothesis could be due to the limited scoring range of the comprehension test, which only encompassed values ranging from 0 to 4. This limited scale lacked the discriminative power necessary to capture subtle variations in the participants' learning performance. Furthermore, it is noteworthy that a significant proportion of the participants, which were all university students, exhibited a high level of prior knowledge on synaptic transmission. Combining these factors, the high prior knowledge base among the participants could have obscured discernable differences in learning between cued and non-cued conditions of the multimedia lesson. This aligns with previous research suggesting that individuals with high prior knowledge typically outperform novice learners (Richter et al., 2018; van Gog, 2014). Moreover, it could be that both the multimedia lesson and the comprehension test were not sufficiently challenging to detect substantial interaction effects between WMC and cueing on learning outcomes. Building upon the latter points, the lack of a significant interaction could be attributed to the relative ease or familiarity of the learning material. Moreover, the distribution of WMC scores was highly concentrated around the mean, resulting in minimal variability among the participants. This could be attributed to the lack of heterogeneity in my sample where the differences in WMC scores were not large enough.

Conclusion

In conclusion the study showed that incorporating cues into multimedia learning is effective in directing learners' attention towards elements relevant to the learning objective. Particularly, the inclusion of cues at the beginning of the lesson proved beneficial in facilitating attention allocation. These findings align with previous research highlighting the positive effects of signaling on attention (Hu & Zhang, 2021; Jamet et al., 2008; Kriz & Hegarty, 2007; Skuballa et al., 2012). Notably, the presence of an order effect in cueing presentation adds newfound insights to the existing literature, as previous studies did not account for this aspect. Specifically, this could have potential implications for designing multimedia lessons encompassing cues, whereby situating cues at the outset of the lesson can better sustain learners' attention, especially for longer lessons. Contrary to prior research (Jamet, 2014; Jamet et al., 2008; Shipstead et al., 2012), this study found no significant effects of WMC and cueing on learning outcomes. The limited research examining the interplay between the differences in WMC and cueing on learning, coupled with the inherent limitations of the current and previous studies, suggests that the expected effects of signaling may not manifest amongst learners with different WMCs. This outcome may be attributed to the evident attention-guiding effect induced by cueing, which could overshadow the potential effects of WMC on learning. Nevertheless, future investigations may benefit from exploring other design principles which draw heavily on attentional control and that could explain differences in learning amongst individuals of different WMC (see

Fenesi et al., 2016). Consequently, while signaling has shown to be effective in directing attention, its potential to engender differences in learning outcomes among learners of different WMCs remains inconclusive. Future studies seeking to delve deeper into this line of inquiry should duly acknowledge the limitations of the present study as well as previous ones, as discussed above. Broadly speaking, conducting further research to investigate the impact of WMC on learning outcomes in attention-demanding multimedia learning environments, can hold significant implications for instruction design and subsequently foster learning for individuals with lower WMCs.

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