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Article

The impact of visual attention on visual working memory

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SUMMARY

The multimodal model of memory proposes that information is passed through three separate memory stores. One type of memory is working memory, which is used to store and manipulate information for a short period. Currently, little is known about working memory and its relationship to attention in adolescents, and our study aimed to address this gap. We investigated whether the information stored in working memory depends on the focus of a person's attention, which is relevant to the classroom environment. For our study, we designed a within-subjects change detection task that examined two variables: 1) attentional cue (image shape, color, or both) and 2) memory load (two, four, or eight items). After participants were given an attentional cue, they identified changes in sequences of colored shapes. We measured behavioral responses using reaction time, accuracy, and working memory capacity. Our first hypothesis was that participants' accuracy and capacity would be higher, while reaction time would be lower, if they were paying attention to only shape or color instead of both. Our second hypothesis was that accuracy and capacity would decrease, while reaction time would increase, as memory load increased. Our results did not line up with our first hypothesis because we found that participants did better when paying attention to just colors compared to shapes or both; however, our second hypothesis was supported by our findings. The findings in this study help us understand the relationship between working memory and attention, with implications for how efficiently students retain new information.

INTRODUCTION

In education, students constantly rely on their attention and working memory to process information, which is crucial for effective learning. Attention is essential for noticing new information in the classroom and retaining it, serving as the vital first step in acquiring knowledge (1). Memory storage enables students to manipulate information for application in new situations (2). For example, when solving a math problem, a student must first attend to the problem and then use memory for calculations. Understanding these cognitive functions is important for improving education, as they form the foundation of learning. Hence, our study focused on the connection between attention and working memory. Previous research has outlined various models for attention and working memory, and we aimed to apply these concepts to students in a school setting to better understand and support their learning processes.

Some researchers have proposed that attention is a process in which information is taken in. It can also be thought of as a limited resource for keeping information "active" and available for use (3-5). Here, we focused on attention as a selection process, prioritizing what information to focus on from a larger set (6). Within this framework of viewing attention as a selection process, there are four different types of attention: selective (focusing on one thing), divided (paying attention to multiple things), sustained (focusing for a period of time), and executive (regulating the focus of attention) (7). Research in humans and non-human primates has shown that using attention to prioritize information impacts brain activity in the visual system because it helps filter out distractions and focus the brain on what's most important (8, 9). The first stage of visual processing (the striate cortex) is not affected by the focus of attention whereas the more complex stages (the extrastriate cortex) are influenced by attention, showing how attention helps the brain filter out irrelevant information later on in the process, allowing it to focus on and remember specific objects (10, 11). However, when there are multiple competing stimuli, attention can influence early visual areas as well (12).

Although working memory and short-term memory are often used as synonyms, they are distinct. Short-term memory holds information briefly, from seconds to minutes, while working memory uses this information to perform tasks and draw conclusions. Baddeley and Hitch were the first to propose the idea of working memory (13). According to their model, there are four parts of working memory: central executive, visuospatial sketchpad, episodic buffer, and phonological loop (13). In this study, we primarily focused on the visuospatial sketchpad, which manages visual and spatial information, and the phonological loop, which manages spoken and written information.

As mentioned earlier, attention is the process of taking in information, while memory is the process of storing that information. According to Atkinson and Shiffrin's multi-store model of memory, sensory information from the environment is first attended to and then stored in short-term memory for a few seconds to minutes (2). When this information is recalled and manipulated, it moves into the working memory. Attention is important for maintaining content in working memory, because it needs to be continually refreshed to prevent decay. The selection of information that enters working memory is monitored by the filter of attention, which prioritizes what is focused on at any given moment. Working memory only holds the information necessary for the current task. A previous study noted that attention generally affects the processing of information from the moment something is noticed and onward (14). Focusing attention on specific environmental

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input increases the likelihood that it will be stored in working memory, though it can still be filtered out. As evidence of the connection between attention and working memory, studies have demonstrated that individuals with higher attentional control also have a higher working memory span (15). Research has also shown that individuals can specifically focus their attention on certain items, requiring continuous focus to retain information within working memory (3). Researchers have noted that the number of items that an individual is paying attention to restricts the ability to process visual information (16). Previous studies have indicated that an individual can only hold three to four objects in their working memory at one time (17-19). Interestingly, multiple features of an object can be retained at one time such as the color and orientation of an item (20).

The purpose of our study was to build on the existing research about the relationship between attention and visual working memory, specifically focusing on adolescents, a demographic that not much research has been done on. We examined how attention and working memory are connected in the visual domain. We also aimed to determine whether the focus of attention influences how much information is retained in working memory. To explore these topics, we designed an experiment in which participants were given a cue to pay attention to either shapes, colors, or both, and then they were shown two sets of images. Participants had to identify whether there was a change between the two sets, and we examined the metrics of answer accuracy, reaction time, and memory capacity. We developed three hypotheses: first, we predicted that participants will be less accurate and take longer to respond when paying attention to more than one attribute compared to focusing on a single attribute. Second, we predicted that if participants have to pay attention to fewer items (meaning a reduced memory load), they will respond more accurately and quickly to prompts. Finally, we hypothesized that there is a saturation point for working memory capacity. For example, participants can remember all presented information when shown two items but are less likely to do so when shown eight items, indicating a limit to their working memory capacity. We found that, contrary to our first hypothesis, participants did better when paying attention to color compared to shapes or both. Our results supported our second hypothesis because we found that as memory load, decreased, participants' accuracy decreased and reaction time increased. We also found that there is likely a saturation point for memory capacity, because when participants were paying attention to both shapes and colors, their capacity went into the negatives, meaning they were forgetting information. Overall, our experiment helped us learn that the focus of attention does have an impact on what we hold in our working memory, and our data on how students best retain information could have future implications for education.

RESULTS

Experimental design

The goal of our experiment was to examine how participants focusing their attention on different attributes affects working memory, while also varying the amount of information they were given at a time. Our main hypothesis was that if participants had to pay attention to a greater number of items and more attributes of those items, they would be less accurate and would react more slowly. To test this, we designed a computer game, where 24 7th and 8th grade participants were shown a set of images and instructed to pay attention to a certain condition: either their color, their shape, or both color and shape (**Figure 1-2**). They then had to answer a yes or no question about each set of stimuli. All participants were tested in all three conditions to ensure consistency across our results. We analyzed their accuracy and reaction time to the question and calculated their working memory capacity. As a reminder, capacity is the amount of information that a person can hold in their working memory at a time. Working memory was tested by varying the number of objects they were shown in each set of stimuli (the memory load), meaning that they could be shown two, four, or eight objects.

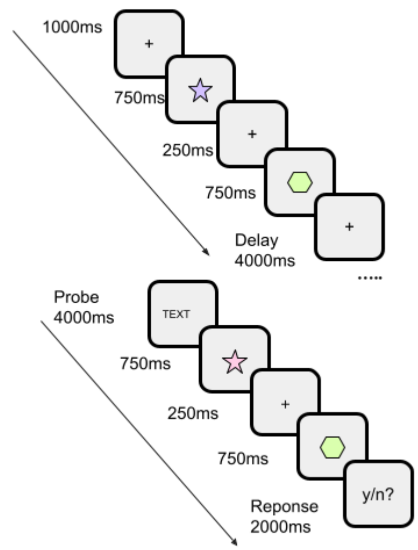

Figure 1. Experimental design of participant study. Participants were instructed to pay attention to the shape, color, or both, and then were shown two sets of images from the stimulus set with a slight pause (designated here by "+") between each image. In between the sets, they were shown a message on the screen (designated here by "Text") asking them to look for a change between the two sets. At the end of the trial, they had to respond yes or no as to whether the two sets were the same (designated here by "y/n").

Participant answer accuracy

Overall, we found that participants' accuracy decreased as memory load increased. Answer accuracy was higher when participants were paying attention to only colors compared to only shapes or both shapes and colors (**Figure 3**). We ran a 3 (load) x 3 (condition) ANOVA to determine whether the differences we saw were statistically significant. We found a significant effect of load ($F(1,23)=10.08$, $p<0.01$), meaning that answer accuracy for all conditions decreased as the load increased. We also found a significant effect of condition ($F(1,23)=24.98$, $p<0.001$). Participants had higher answer accuracy in the color-only condition compared to shape or color and shape conditions. The image, shape, and color (both) condition had a slightly lower answer accuracy than color and shape alone, but it was similar to the shape condition. There was a significant difference when doing a comparison between shapes versus colors ($p<0.05$) as well

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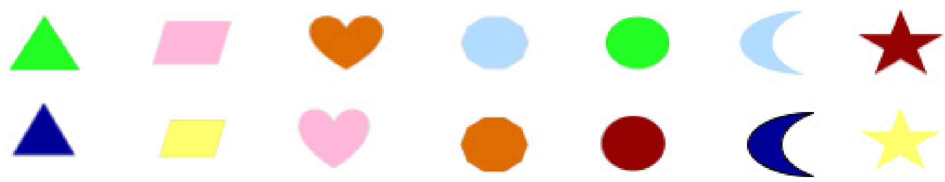

Figure 2. The stimulus set of the study. There were 14 possible items that could be shown to participants, with 7 different colors and shapes. Participants were shown groups of these items and told to pay attention to the color, shape, or both. All the items are colorblind friendly.

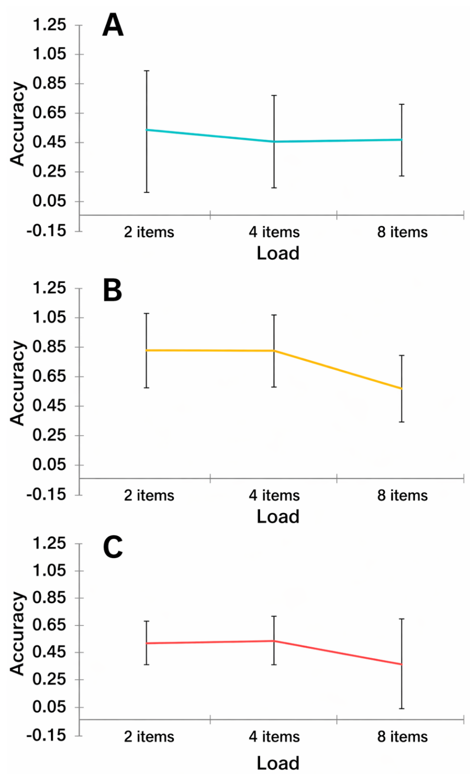

Figure 3. Participant answer accuracy. Accuracy of participants in detecting whether or not the two sets of items shown were the same, based on which condition they were attending to: **A)** shape (turquoise), **B)** color (yellow), or **C)** both shape and color (red). Condition refers to a certain aspect of the images that participants are told to pay attention to while load refers to the number of images displayed in the game. Data is shown as mean ± SD. 3x3 ANOVA with independent variables of condition and load showed a significant effect of load ($p<0.01$) and condition ($p<0.001$). 24 participants participated in the study and were tested across all three conditions.

as colors versus both ($p<<0.05$), showing that condition had a statistically significant effect on answer accuracy. Participants were much more accurate when paying attention to colors compared to the other two conditions. We did not find a significant load x condition interaction ($F(1, 23)=3.22$, $p>0.05$), meaning that although it may look like there is a correlation between those two variables, it is not statistically significant.

Participant answer reaction time

Overall, participants' reaction time increased as memory load increased (3 (load) x 3 (condition) ANOVA, $F(1,23)=4.828$, $p<0.05$, **Figure 4**). There was a significant different when comparing participants' reaction time at load two versus at load eight (t-test, $p<0.05$). However, we did not find a significant effect of condition (3 (load) x 3 (condition) ANOVA ,$F(1,23)=1.14$, $p>0.05$), or a significant load x condition interaction (3 (load) x 3 (condition) ANOVA, $F(1,23)=0.28$, $p>0.05$).

Participant working memory capacity

Using 3 (load) x 3 (condition) ANOVA, we did not find a significant effect of load on participant memory capacity ($F(1,23)=3.13$, $p>0.05$). We also did not find a significant load x condition interaction ($F(1, 23)=2.75$, $p>0.05$). However, we found a significant effect of condition on capacity ($F(1,23)=5.33$, $p<0.05$), which means that memory capacity changed significantly depending on condition. There was a significant difference when doing a comparison between shapes versus colors ($p<0.05$) as well as colors versus both ($p<<0.05$), showing that capacity was significantly affected by condition. Memory capacity decreased for participants when they were paying attention to only shape or color but stayed the same for participants when they were paying attention to both when comparing capacity at two versus four items (**Figure 5**). When comparing participants' memory capacity between a memory load of four items to eight items, the pattern of results for memory capacity was the opposite. Memory capacity stayed the same when participants were paying attention to shape or color but declined when they were paying attention to both. In general, participants attending to color had a slightly higher memory capacity overall while those attending to both color and shape had the lowest memory capacity.

Participant reflections

We asked participants two reflection questions: which condition (color, shape, or color and shape) was the easiest for them and which was the hardest. We found that 67% of participants indicated that only paying attention to color was easiest for them, 21% said only paying attention to shape was the easiest, and 12% indicated that paying attention to both color and shape was the easiest (**Figure 6**). Additionally, 46% of participants found the "both" condition to be the hardest, 37% indicated shapes were the hardest, and 17% found colors to be the hardest (**Figure 6**).

DISCUSSION

Our study explored how a person's focus of attention impacts their ability to hold information in their working memory. Our central hypothesis was that as participants had to pay attention to more attributes of images (both shape and color) or a greater number of images, their answer accuracy

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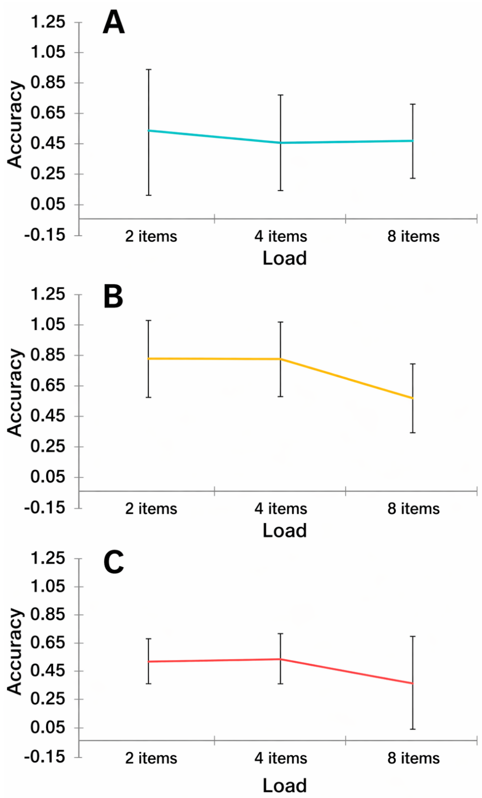

Figure 4: Participant reaction time. These graphs show the time taken by participants to say whether or not the two sets of items shown were the same, based on whether they were attending to: **A)** shape (turquoise), **B)** color (yellow), or **C)** both shape and color (red). Condition refers to a certain aspect of the images that participants are told to pay attention to while load refers to the number of images displayed in the game. Data is shown as mean ± SD. 3x3 ANOVA with independent variables of condition and load showed a significant effect of load ($p<0.05$). 24 participants participated in the study and were tested across all three conditions.

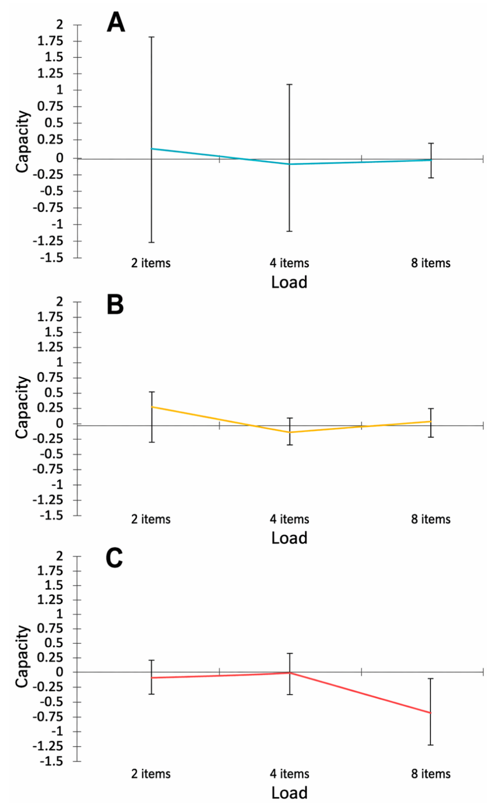

Figure 5. Participant memory capacity. These graphs show the capacity of participants' memories based on whether they were attending to: **A)** shape (turquoise), **B)** color (yellow), or **C)** both shape and color (red). Condition refers to a certain aspect of the images that participants are told to pay attention to while load refers to the number of images displayed in the game. Data is shown as mean ± SD. 3x3 ANOVA with independent variables of condition and load showed a significant effect of condition ($p<0.05$). 24 participants participated in the study and were tested across all three conditions.

would decrease, their reaction time would increase, and they might reach a saturation point for their working memory capacity. In our experiment, participants had to detect whether there was a difference between the two sequences of images they were shown, and the two variables we controlled were how many images they were shown and what aspects of those images they had to pay attention to. We examined participants' answer accuracy, reaction time, and memory capacity and found that participants did better when paying attention to color compared to shapes or both, which did not support our hypothesis. We also found that participants had a higher accuracy and lower reaction time for smaller numbers of items, which did back up our hypothesis.

Our findings provide several insights. First, the study enhances our understanding of how attention affects working memory. We discovered that the demands on attention influence how much information is stored in working memory, aligning with Atkinson and Shiffrin's multimodal model of memory (2). As memory load increased, we observed a decrease in answer accuracy and capacity, while reaction time increased, suggesting that higher memory loads make information retention more challenging. Participants had higher answer accuracy when remembering only colors compared to only shapes or both color and shape, suggesting that certain features may be easier to remember than others. Our study contributes to existing research on attention and working memory by providing data from real students, which can impact strategies to enhance educational outcomes.

The participants in our study were all 7th and 8th grade students, a group for which little research has been conducted on how their attention impacts their working memory. Previous research on different age groups, such as a study comparing younger and older adults' abilities to remember various words, found that both groups performed similarly in remembering the most important information (21). However, young adults were able to recall additional pieces of information, especially certain specific values, that older adults were not able to (21). Building on these findings, another study revealed that working memory capacity and the ability to selectively focus attention were lower in older adults compared to younger adults (22).These studies show the differences between younger and older adults, but not much research has been done on those below that age. School-age children and teenagers are important age groups to study for this type of research because the relationship between attention and working memory has implications for the field

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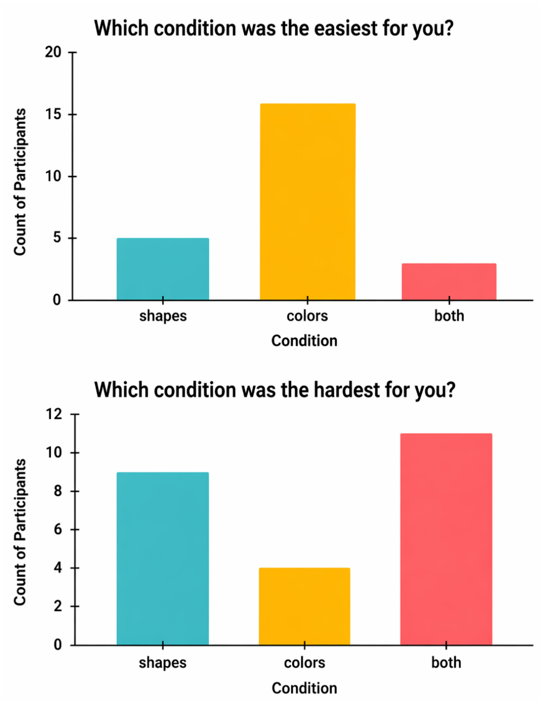

Figure 6. Participant reflection questions. Reflection questions asked to participants after they completed the study on which condition was the easiest for them and which was the hardest. A total of 24 participants responded to each question.

of education. Our study provides valuable insight into the age group of pre-teens, whose attention and working memory are still in development.

We hypothesized that the participants' answer accuracy would decrease and reaction time would increase when attending to both shape and color compared to attending to just one. While the ANOVA revealed no significant effect of condition on reaction time, there was a significant effect on answer accuracy. Interestingly, participants performed much better in the color condition compared to the shape or both conditions contrary to our prediction that they would perform similarly for shape and color and worse for both.

Our second hypothesis suggested that participants' answer accuracy would decrease and reaction time would increase as memory load increased since they had to pay attention to more items. This hypothesis was supported by our findings, which showed a significant effect of memory load on both answer accuracy and reaction time. As memory load increased, accuracy decreased, and reaction time increased In our third hypothesis, we anticipated that the participants' working memory would reach a saturation point, beyond which they would be unable to hold additional information. We expected that as memory load increased, participants' capacity would decrease due to an overwhelming number of items to remember. However, we did not find a significant effect of load on capacity. We also hypothesized that in the "both" condition, where participants had to remember double the amount of information, their capacity would decrease. This was confirmed, as there was a significant effect of condition on capacity. We found that the shape and color conditions had higher capacities than the "both" condition. Unexpectedly, participants attending only to color had a slightly higher capacity than those attending only to shape. We believe that the capacity for the "both" condition might have gone into the negatives because participants reached the limits of their working memory capacity and started forgetting information.

Our study had some limitations that might have affected the results. Firstly, the use of stimuli (shapes and colors) may have provided us with a limited understanding of the relationship between attention and working memory because when you learn new information in the real world, it has many other attributes besides simply shape and color (19). Moving forward, it would be interesting to conduct this study by comparing other types of stimuli such as hearing versus vision. Additionally, with only 24 participants, our results are not as robust as they would be with a larger sample size, since outliers could have a more significant impact on the data.

An interesting future direction for our study would be to collect data from other age groups, such as young children and adults, to compare results and learn more about the effects of age on attention and working memory. Another avenue would be to run additional statistical tests, like t-tests, to compare results across conditions at a given memory load. Increasing the number of participants would also help us draw more accurate conclusions by revealing overarching patterns and mitigating the impact of outliers. We could also examine the effect of demographics on our results, such as whether one demographic of participants preferred colors while another preferred shapes. One intriguing question that emerged is, "Why did participants perform so much better with colors than with shapes?" We can explore this further by modifying our experimental design, such as by using more muted colors to see if the reason participants remembered colors better was because they were more vivid and noticeable.

There are still several scientific questions remaining, such as whether our data differs across age groups and stages of development, or whether it is possible to improve people's working memory capacity with training. However, in broad terms, this study has significant implications for education, as our understanding of the relationship between attention and working memory can be leveraged to enhance teaching methods to help students absorb more information. By understanding how students' focus impacts their memory retention, educators can better guide students' attention to optimize learning (23). If students can effectively direct their attention to retain more information within a given timeframe, then education becomes more efficient and the students' overall school experience improves. This is part of a bigger effort to connect our understanding of how the brain learns with what goes on day-to-day in the classroom.

MATERIALS AND METHODS

Context for research study

This project was conducted in the Brainwave Learning Center (BLC), a research-practice partnership between Synapse School and Stanford University (24). The BLC has a program where a group of middle school students at Synapse School conduct their own studies as research assistants with guidance from the Stanford researchers (25). The authors of this paper are two of the students in the middle school research assistant program, along with their two mentors.

Participants and materials

For our experiment, we recruited 7th and 8th grade students (12-14 years old) in Menlo Park, California. We had a total of 24 participants in our study, 11 males and 13 females. All the participants had corrected or normal vision because our study was vision-based. All components of this research were approved by the Stanford University Institutional Review Board (IRB #50742).

Stimuli

We used seven shapes, each presented in two color-blind-friendly colors. The colors were specifically chosen from a palette of colorblind-friendly colors by the Jackson Lab at the University of Wisconsin-Madison (26). Each shape appeared in two colors to control the variables; if there was a color change, the shape remained the same. This design allowed us to focus on color changes without introducing additional variables. The shapes and colors were presented in various random orders throughout the experiment. The changes occurred at different points within the stimulus set, rather than always at the beginning or end, to avoid any pattern biases.

Experimental design

Participants played a computer game where they were instructed to answer questions about a set of stimuli as fast and accurately as possible. The computer game we designed had three main blocks of attentional cues where the participant focused on the shape, the color, or both the shape and the color (referred to later as "both") of the objects presented. We referred to these attentional blocks as conditions and counterbalanced it so that there were six different possible orders that these conditions could be displayed in to ensure the order in which the conditions were displayed to a participant did not play a role in the results. After being told which condition they were supposed to be focusing on, a sequence of color shapes (either two, four, or eight shapes, which we refer to later as the load) was shown on the screen. After a delay, the same sequence of shapes was shown, this time with a possible change in one of the objects relating to the condition they were told to focus on. The participant was then prompted to answer the yes or no question to indicate whether there was a change between the first and second set of shapes presented. Each participant was tested in all 3 conditions resulting in approximately a 30-minute session. As the last step in the research session, we asked participants what the easiest and hardest condition was for them, in order to learn about their experience of participating in the game.

Data analysis

We tracked three metrics: answer accuracy, reaction time, and working memory capacity. We calculated answer accuracy based on the proportion of correct responses in each condition. Reaction time was calculated as the duration that participants took to respond (in milliseconds) to the yes or no question. Working memory capacity was calculated based on Cowan's K (27). Capacity represents the amount of information that fits within a person's working memory, and we tracked it because we wanted to see whether participants' memory capacity reaches a limit as we present the participant with more information. The formula we used to calculate capacity in this study was $k = n(h+cr-1)$, where k was the working memory capacity estimate; h was the hit or "saying yes when the correct response is yes"; cr was the correct rejection or "saying no when the correct response is no"; and n was the number of stimuli presented.

We analyzed our data by taking the averages of reaction time, answer accuracy, and capacity estimates for each load and condition, within each participant's data. For the "both" condition, we separated the data into instances where the color changed and instances where the shape changed. We analyzed the data of the two groups separately to see whether there was a difference in participants' results but then averaged them to summarize the "both" condition. We took averages of each metrics across participants and created graphs (**Figures 3-5**).

Statistics

We ran a 3x3 ANOVA to analyze variance and set load and condition as within subject variables. We used the ANOVA results to determine which variables had significant effects on the data. Since the ANOVA revealed overall significant effects for certain variables but did not specify where those differences occurred, we conducted pairwise comparison t-tests to determine which specific groups differed significantly from each other **(Tables A1-A3)**. Our threshold for significance was $p<0.05$.

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APPENDIX

Load	*p*-value	Condition	*p*-value
2 versus 4	0.660483	Shape versus Color	2.824938e-08
2 versus 8	0.003189049	Shape versus Both	0.3043924
4 versus 8	0.006190368	Color versus Both	6.641178e-16

Table A1. Pairwise comparison t-tests for participant answer accuracy. These tables show the *p*-values from our t-tests for all pairwise comparisons related to answer accuracy—both between different loads (e.g. load 2 versus load 4) and between different conditions (e.g. Shape versus Color). Condition refers to a certain aspect of the images that participants are told to pay attention to while load refers to the number of images displayed in the game.

Load	*p*-value	Condition	*p*-value
2 versus 4	0.101689	Shape versus Color	0.1585804
2 versus 8	0.00428687	Shape versus Both	0.4014662
4 versus 8	0.1707554	Color versus Both	0.5219727

Table A2. Pairwise comparison t-tests for participant reaction time. These tables show the *p*-values from our t-tests for all pairwise comparisons related to reaction time—both between different loads (e.g. load 2 versus load 4) and between different conditions (e.g. Shape versus Color). Condition refers to a certain aspect of the images that participants are told to pay attention to while load refers to the number of images displayed in the game.

Load	*p*-value	Condition	*p*-value
2 versus 4	0.6504234	Shape versus Color	0.01882409
2 versus 8	0.04173958	Shape versus Both	0.2370975
4 versus 8	0.06798315	Color versus Both	4.504662e-12

Table A3. Pairwise comparison t-tests for participant memory capacity. These tables show the *p*-values from our t-tests for all pairwise comparisons related to memory capacity—both between different loads (e.g. load 2 versus load 4) and between different conditions (e.g. Shape versus Color). Condition refers to a certain aspect of the images that participants are told to pay attention to while load refers to the number of images displayed in the game.