Precision of Visual Working Memory: How Colours and Sizes Decay over Time

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Abstract

Visual Working Memory (VWM), the cognitive function that allows us to temporarily store, maintain and retrieve visual information has been under investigation for a long time. The two most common theories that try to explain how VWM works are the discrete capacity model and the limited resource model. The former explains VWM in terms of “slots” to be filled with visual information that can be retained effectively as long as the visual items do not exceed a certain “slot-limit”, whereas the latter explains VWM in terms of a pool of resources to be allocated to visual information that can be retained more effectively if they are less complicated. The present study aims to investigate whether attention, time delays and amount of visual information influence the retention of visual information. Fourteen participants from Germany had to memorize different visual features of up to four visual items for time delays that varied between one and nine seconds. Moreover, the experiment was divided into three different blocks. In the first block, the participants were asked to memorize the colour of the visual items, in the second the size, and in the third both colour and size. The data analysis showed that focusing on one feature instead of two, as well as the number of presented visual items, both had a significant effect on recall accuracy, which supports the limited resource model and gives more insight into how VWM decay functions. Decay time itself had no significant effect on recall accuracy, supporting the idea that other mental processes that occur during a given timeframe are the reason for decreased recall precision.

Introduction

To a very great extent, humans are visual creatures. The sense of vision is regarded as the most complex and highly developed brain-function for most mobile creatures (Gerrig & Zimbardo, 2008). As people strive toward their goals, they rely on processing, storing or retrieving visual information. Therefore, it is not surprising that the understanding of both vision and memory has been the focus of substantial scientific research. Visual working memory (VWM) is the combination of these two concepts and is defined as the cognitive function that allows us to temporarily maintain, store and retrieve visual information (Olivers & Roelfsema, 2020). Although VWM is clearly defined, there has been an ongoing debate in the scientific community regarding the operation and capacity of this function. The present study aims to investigate factors that could possibly influence how accurately visual information is maintained and retrieved from the VWM.

Since VWM is a component of working memory, theories about working memory also apply to it. For example, a common view is that the VWM has a certain number of “slots”, which can hold individual informational items. Miller (1956) indicated in his research that this number is seven plus or minus two items. However, some recent research into this topic has concluded that this number of slots is smaller than previously thought, namely four items (Cowan, 2001). Regardless of the precise limit, the common theory still holds that if a person must memorize more than a given number of items, then some items will be remembered less accurately or forgotten completely. The extent to which items will be blurred or erased from VWM, therefore, increases with every item over that limit. This common theory is hence called the discrete-capacity model; The VWM has a discrete capacity, it can be filled with items up to that capacity, and storing items beyond that capacity will result in reduced recall accuracy (Luck & Vogel, 1997).

Recent research questions this notion and posits that it is more likely that VWM has a limited pool of resources that can be assigned to maintain and store information (Ma, Husain & Bays, 2014), a view that was coined the limited resource model. How many resources are allocated and how well it is encoded, therefore, depends on the complexity of the informational item. Keeping complex items in VWM will exhaust more resources, consequently allowing for fewer items to be stored effectively. If the items are simple and require few resources, more of them can be stored in VWM.

Time is believed to significantly predict recall accuracy in VWM. According to one theory, items in the VWM may “die a sudden death” (Zhang, & Luck, 2009), meaning that once a time-limit has been surpassed, some items are going to disappear from the VWM slots. This is in line with the discrete-capacity model, as it prioritizes the quantity of the slots instead of the quality of the items in order to explain a decline in recall accuracy.
Another theory suggests that items in the VWM could be gradually deteriorate over time (Barrouillet, Portrat, Vergauwe, Diependaele, & Camos, 2011; Rademaker, Park, Sack, & Tong, 2018). Therefore, recall accuracy would depend on the length of the time-interval between storing and retrieving visual information (decay time), and such a mechanism would give credit to the limited resource model. The complexity of the items would decrease as time passes until enough time has passed for the item to disappear completely from the VWM. Important to note is that these studies explained the degradation of the items as a consequence of noise accumulation during the maintenance phase. Therefore, items might degrade or disappear from the VWM, but the reason may not be time on its own but other processes that occur during that timeframe. The temporal distinctiveness model supports this notion also during the encoding process. It presumes that longer time-

intervals between items will lead to less interruption of the encoding process by the previous items and thereby increase recall accuracy (Souza, & Oberauer, 2015).

A factor that could moderate the observed effect of time on recall accuracy might be attention. The items that are mostly paid attention to will more likely, as well as more precisely, remain in the VWM (Brummerloh & Müller, 2019). Similarly, if the item consists of multiple features and the observer is asked to pay attention to a particular feature, that feature will more likely remain in the VWM and the features that have not been paid as much attention to will decay or vanish more quickly (Markov et al., 2019). The effect of attention on the VWM is not limited to the encoding process but is also required for the maintaining process. Items that have already been encoded are being kept in memory by repeated and active attention to their representations in the VWM, which is why Awh et al. (2006) argue that working memory and attention are closely intertwined.

In regard to the current study, it is hence hypothesised that attention can explain the decline in recall accuracy, whereas time on its own cannot. It is also hypothesised that an increase in the volume of memorised information will lead to decreased recall accuracy and that such a decrease is gradual instead of abrupt.

Methods

Participants

Fourteen adults of German nationality participated in the current study (Mage:24, range: 19-48, 8 males, 6 females). All data could be included in the analysis. The experiment got approved by the University of Twente Faculty of Behavioural, Management and Social Sciences ethics committee under the approval code of 220991. All participants gave written informed consent.

Materials

The experiment was conducted using a Lenovo Yoga 530-14IKB with a 14-inch display, a resolution of 1920x1080 pixels and a screen ratio of 16:9, running Windows 10. The participants sat roughly 50cm away from the screen. The code was programmed in python 3.8 using Visual Studio Code 1.67.2. The Stimuli consisted of rectangles with a side ratio of 16:9 and those stimuli differed in colour and size. The values of the dimensions that were used in the main experiment were generated by the participants in a pretest to correct for individual differences in perception. A more detailed account of the stimulus generation is given in the procedure section.

Procedure

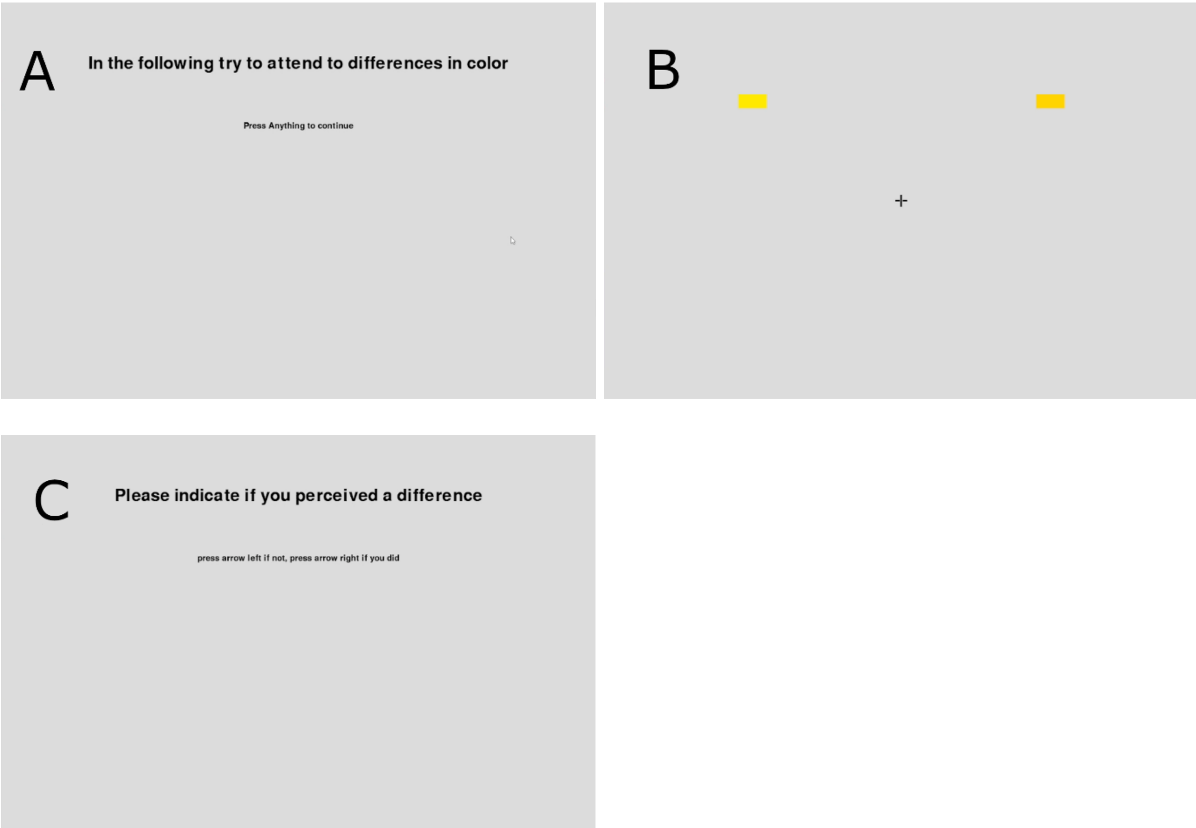
The participants were handed a consent form that informs them about the purpose of the study, how their data will be used, and their rights to withdraw at any point during or after the experiment. After they consented to participate in the study, they were introduced to the pretest that generated the visual stimuli that they personally could consistently distinguish, and which were used for the main experiment.

More precisely, the pretest consisted of two blocks that generated seven stimuli for both visual features. During the first block, the participants had to distinguish between colours (Figure 1A.). After a countdown, a fixation cross appeared in the middle of the screen, alongside two coloured rectangles on each side (Figure 1B.). These rectangles had either the same or different colours. Participants were told to focus on the fixation cross and indicate whether they perceive a difference in colour between the two rectangles (Figure 1C.). In the code, colours were represented using the HSV model (Hue, Saturation, Value). The default colour had a hue degree of 0°, a saturation of 100% and a value of 100%.

As such, the difference between colours was generated by increasing the hue value of one colour. The first colour to be distinguished by the participants had an increase in hue by 5°, and to add this colour to the set of seven stimuli, the participants had to correctly answer five times in a row. During that time, the colours differed three times from one another and were identical twice. If the participants gave a wrong answer, then the hue degree of the colour was increased by 5° again and this process was repeated. If the participants answered five times correctly, however, that colour was added to the colour set and became the new default colour, with the difference in hue to the second colour being reset to 5° again. The first repetition of this process added two stimuli to the set, the default colour with a hue degree of 0° and the first colour that the participant was able to distinguish next to that colour. Once all seven colours were added to the colour set, the participants moved on to collect seven sizes for the size set. Here, the default size was 70x35 pixels and the second stimuli was generated using a size multiplier of 1.05. For every wrong answer, the size multiplier was increased by 0.05. Likewise, participants had to correctly answer five times in a row for the size to be added to the size set and after each addition to the set, the currently modified size became the default size and the size modifier was reset to 1.05. Just as with the colour set, the first default size of 70x35 pixels was added to the set after the participants generated a size that they were able to differentiate from the default one. After the participants finished this pretest, they were asked to take a break of five minutes to rest their eyes and recover their ability to concentrate.

Figure 1

Depiction of the pre test during the collection of colour stimuli

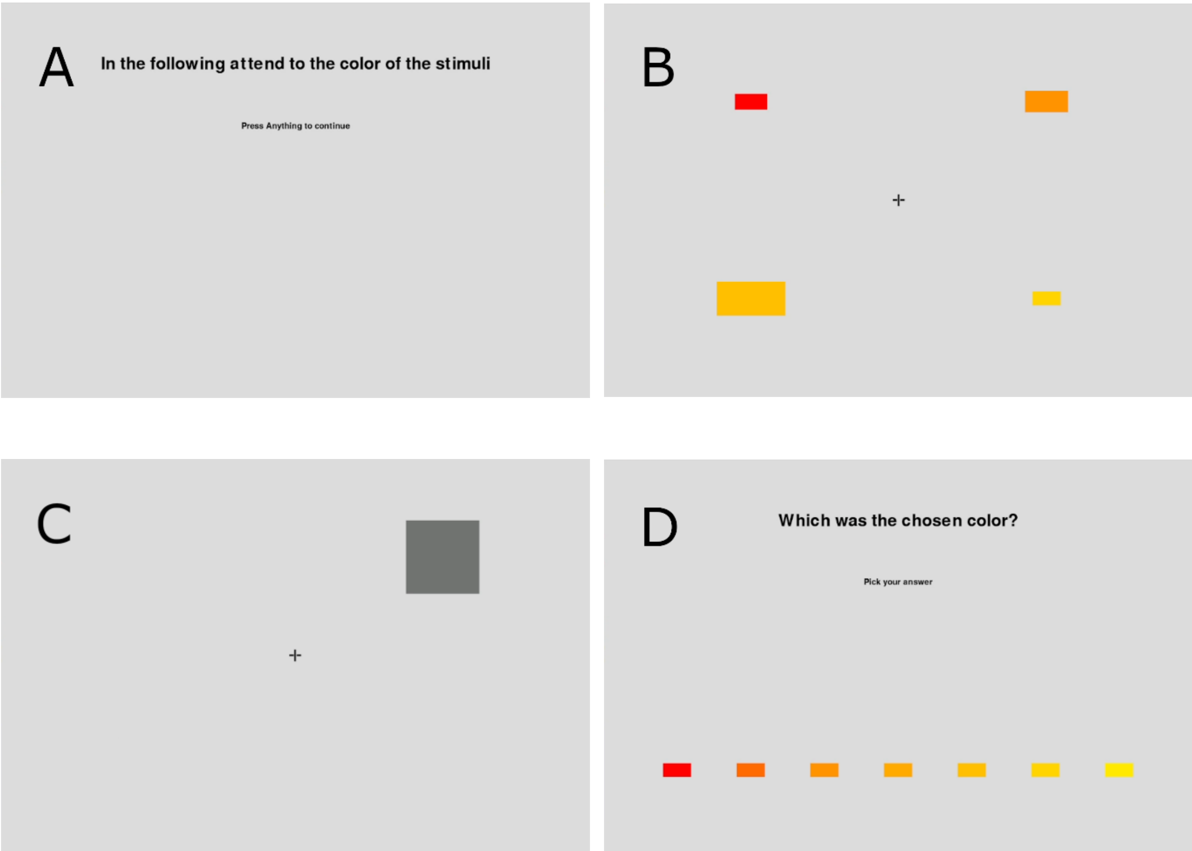


Note. At the start of the colour block, the participants were notified that they had to attend to the differences in colour (A). After a countdown of three seconds in the middle of the screen, the visual stimuli are presented for one second (B). Subsequently, a screen appears where participants are asked to indicate whether they perceived a colour difference or not (C).

After the short break, the participants moved on to the main experiment, wherein they had to work through three different blocks, each with 18 trials. Moreover, each block had its own attentional instruction that indicated which visual feature the participant had to focus on (Figure 2A.). In the first, they only had to attend to colour, in the second only to size, and in the third to both colour and size. Each trial started with a three second timer that indicated when the visual stimuli would appear on the screen. In the subsequent presentation, one, three or four randomly selected visual stimuli from the pretest set appeared on the screen for one second, although with no possibility of one visual stimulus to be equal to another in either colour or size (Figure 2B.). After the presentation, either one, three or nine seconds elapsed, and a gray box appeared at the place of one of the stimuli they had to remember the feature of (Figure 2C.). The participants proceeded to a recall screen, where they were asked to click on the colour or size of the visual stimuli that had been at the place of the gray box during the presentation screen. All nine options were the same visual stimuli that were generated in the pretest and in the order that they were generated (Figure 2D.). In case they were going through the third block, the participants did not know which visual feature they would be asked to recall. In that regard, the recall screen was random, although nine times it pertained to colour and the other nine times to size. After each block was finished, participants were asked to take another break and the main experiment was repeated one more time. The whole experiment, including the pretest and initial explanation of the study, took about an hour to complete. At the end, participants were asked about any issues they experienced with the experiment or if they have any further questions.

Figure 2

Depiction of the main experiment during the attentional condition of colour



Note. At the start of each block, participants were notified of which stimuli feature they had to attend to (A). After a countdown of three seconds in the middle of the screen, the visual stimuli were presented for one second (B). The decay time elapsed, and a gray box appeared at the place of one of the presented stimuli (C). Lastly, a recall screen appeared where participants were asked to indicate the colour that stimulus had (D).

Data Analysis

The dataset generated by the program needed to be recoded, as the visual features of the stimuli, hue degree and size, were stored in raw values. To allow for these data to be appropriately analysed, they had to be converted to fit an ordinal scale. In the case of colour, for example, hue degrees such as 0°, 25°, 30°, 40°, 55°, 60° and 80° were converted into values between 0 and 6. More specifically, 0 for 0°, 1 for 25°, 2 for 30° and so on. The inaccuracy of an answer (error distance) was calculated by subtracting the value of the given answer from the value of the required answer and taking its absolute value. This transformation may lead to a violation of the assumption of normally distributed data, however, the methods used in the subsequent analysis are fairly robust to this violation and it should not affect the validity of the findings. Lastly, the mean error distance was calculated for each combination of the variables (e.g., focused attention, 1-second decay, 1 presented stimuli).

To see if the accuracy of the participants could be partially explained by the participants guessing the answer, a one-sample *t*-test for each possible combination of variables was conducted. The null hypothesis that there will be no significant difference between the restricted error distance means and the average error distance can be stated. Given that the answeres were converted to values between 0 and 6, the average error distance that could be observed if the answers were given randomly is 3.

The next step was to find out whether the number of presented stimuli, decay time and attentional instructions had an effect on the recall accuracy of the participants. For this, a 2 (focused attention, mixed attention) x 3 (1-second decay, 3 seconds decay, 9 seconds decay) x 3 (1 presented stimuli, 3 presented stimuli, 4 presented stimuli) repeated measures ANOVA was conducted.

Results

Above Chance Level Performance

The one-sample *t*-tests that compared the error distance means for each variable combination with the chance-based, average error distance (=3) displayed that all error distance means were significantly lower than the average error distance value. The largest divergence from chance was observed for the focused attentional instruction with 9 seconds of delay and one presented stimulus, Mdiff = -2.553, $t(84) = -28.827$, $p < 0.001$, whereas the smallest divergence from chance was observed for the mixed attentional instruction with 9 seconds of delay and four presented stimuli, Mdiff = -1.70, $t(45) = -6.992$, $p < 0.001$. Hence, the performance of the participants deviated significantly from being based on chance.

Number of Presented Stimuli, Decay Time and Attentional Instructions as Influencing Factors of Recall Precision

The three-way repeated measures ANOVA was used to investigate the effect of the attention conditions (focused, mixed), decay time (1 second, 3 seconds, 9 seconds) and number of presented stimuli (1 stimuli, 3 stimuli, 4 stimuli) on error distance showed several significant one-way interactions. The attentional instruction had a significant effect on error distance $F(1,954) = 16.103$, $p < 0.001$. The number of presented stimuli also had a significant effect on error distance $F(2,954) = 15.794$, $p < 0.001$. However, decay time did not have a significant effect on error distance $F(2,954) = 0.567$, $p = 0.693$. Moreover, the ANOVA showed no significant two-way or three-way interaction effects. Even in the interaction between attentional instruction and the number of presented stimuli, the conditions seem to significantly affect error distance only by themselves, not in combination with each other $F(2,954) = 1.079$, $p = 0.499$.

The mean error distances increased based on the attentional instruction and also on the number of presented stimuli. More precisely, the focused attentional instruction had an error distance mean (0.646; CI: [0.578, 0.714]) lower than that of the mixed attentional instruction (0.920; CI: [0.824, 1.017]) (Figure 3.). Similarly, the average error distance for one presented stimulus (0.611; CI: [0.508, 0.713]) was lower than the error distance mean for three presented stimuli (0.799; CI: [0.695, 0.903]), with both of these averages also being lower than the one for four presented stimuli (0.940; CI: [0.839, 1.040]) (Figure 4.).

Figure 3

The mean error distance for focused and mixed attention with 95% CI Error bars

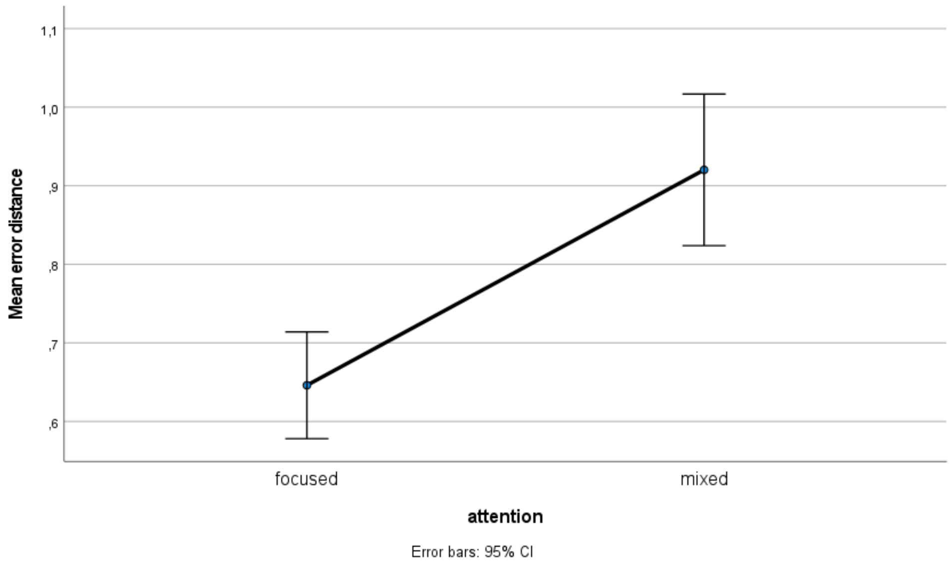
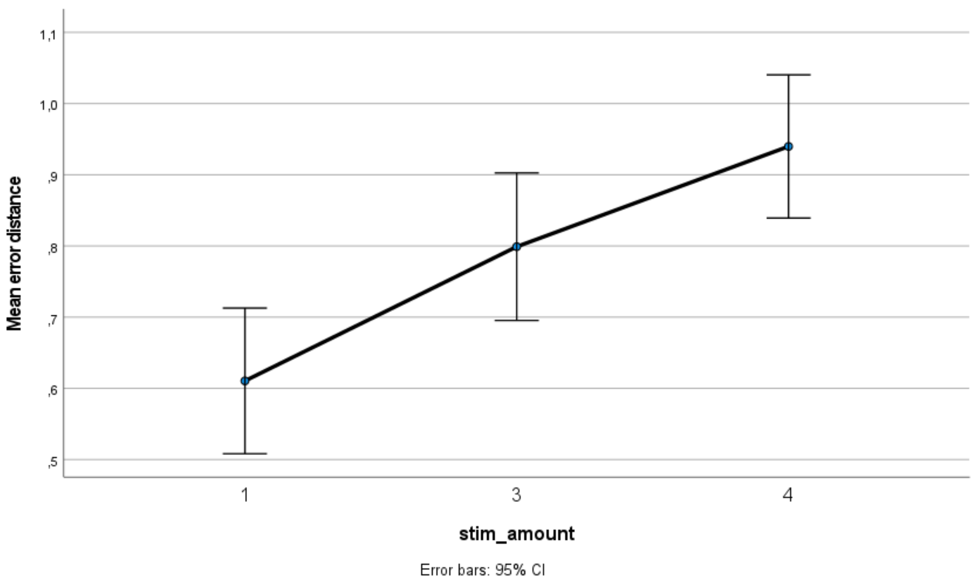


Figure 4

The mean error distance for one, three and four presented stimuli with 95% CI Error bars



Discussion

The aim of this study was to investigate factors that could possibly influence how accurately visual information is maintained and retrieved from the VWM. Consequently, two hypotheses were stated. First, that attention can explain the decline in recall accuracy, whereas decay time on its own cannot. Second, an increase in the volume of memorised information will lead to decreased recall accuracy, and such decrease is gradual instead of abrupt.

The first hypothesis can be accepted, as the results of the analysis showed no significant sudden or gradual decline in recall accuracy based on decay time alone, at least, for timeframes between one and nine seconds. Attention, however, had a significant effect on recall accuracy, which supports the findings of Brummerloh and Müller (2019). Furthermore, research into this topic has already proposed that it is not time itself that leads to the deterioration of visual stimuli in VWM, but instead the result of other processes that happen during that timeframe, such as noise accumulation. This current study provides support for attention to be at least one factor that influences the deterioration of visual stimuli during a given timeframe.

The second hypothesis can also be accepted, as the number of presented stimuli gradually decreases the recall accuracy of the stimuli features. According to the discrete capacity model, there should be a certain number of slots in VWM that can be filled with items to be memorized with no impact on recall accuracy until the limit has been exceeded (Zhang, & Luck, 2009). Nonetheless, the results of the current study do not support this notion. A significant decrease in recall accuracy can already be observed between one and three visual stimuli, something that should not be likely for either the four-item limit (Cowan, 2001) or the seven plus-minus two-item limit (Miller, 1956). Moreover, as the complexity of the items increases, that is, with participants having to memorize up to eight visual features in the mixed attentional instruction, the recall accuracy keeps gradually decreasing. According to the discrete capacity model, it should not matter that the items are more complex, as even with eight visual features, there are still four individual items that can be filled in the available slots. Consequently, the fact that the observed decrease in recall accuracy is gradual, and persists as the items gain more complexity, supports the limited resource model.

Limitations

Concerning the limitations of this study, during the main experiment, some participants noted that it would be easiest to remember the most extreme values. While it is equally difficult to discern the five values in the middle that vary slightly, the first and last options did not need to be compared against two similar values, but just one. This may have influenced the recall accuracy to be less affected by attention, decay time or number of stimuli, as an extreme value would most likely to be chosen correctly. Including options that are never correct at the extremes might have solved this issue if the participants would not notice that these values never actually appear during the presentation phase.

Another possible limitation could be in the way the pre test was coded. More specifically, if participants were presented with two identical values, but indicated that they were different, the difference multiplier still increased the difference between the two stimuli that had to be distinguished in the current set. This led to some values being more easily distinguished from one another. If the code did not increase the difference after a wrong answer for equal values, then all values collected by the participant would have been perceptually just noticeably different.

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