On the limits of short-term memory when exploring websites

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Abstract

This study examines the cognitive limits in change detection on web pages, specifically focusing on the number of items and the type of feature change that affects individuals' ability to detect changes. Previous research has suggested the use of Miller's magical number of seven plus or minus two in web design. However, considering new constraints, this study aims to determine the actual cognitive limits in a web page environment. The experimental part utilizes Change Blindness (CB) and presents participants with displays containing varying numbers of items and different types of changes. The main research question addresses the threshold at which individuals miss a change, while a secondary research question explores the relationship between the type of change and change detection ability. The results indicate that the number of items and change conditions significantly affect change detection. Other further analyses revealed specific differences between the different levels of the factors. The findings provide insights into the cognitive limitations and factors influencing change detection on web pages, offering implications for web design and user experience considerations.

Keywords: visual working memory, change blindness, websites, number of items, change condition

On the limits of short-term memory when exploring websites

From the creation of the email platform in 1972 through the release of the first smartphone in 2007 (Mannix & Hall, 2017), the Internet and the World Wide Web have become two of the most important platforms for people to access and view information (Council et al., 1999). At the time, there are more than 1.5 billion websites on the internet, with the 1 billion mark being surpassed in 2014. Despite the huge quantity of web pages, only about 10% are still active, with an estimated 200 million (Bednarz, 2019). To have a successful website and be accepted by web users, one must use the power of web design which is a key factor for the previously mentioned traits (Flavián et al., 2009).

The human-computer interface, or HCI, is critical for user-web interaction. It is the tool that permits information to be sent between the two specified ends (Ma et al., 2022). Ma et al. (2022) claim that interface aesthetics play an essential part in feature retrieval, but they also have an impact on other variables such as productivity and learnability. Furthermore, cognitive abilities such as working memory and attention are important while interacting with a computer interface.

Working memory, according to Peterson and Berryhill (2013), is a method of obtaining information, more precisely the temporary storage of the momentarily available information. However, in terms of the aesthetics of a web page, the visual working memory (VWM), is a better representative of the working memory. VWM is a component of the working memory and is best defined as a cognitive function that uses visual information to momentarily maintain, store and retrieve the data that has been observed (Renner, 2022). But the limitations of the VWM have been a reason to debate for years.

Thus, through time, a few theories have been held as explanations of the VWM power. The most widely known one was created by Miller (1956). It states that the VWM has a maximum number of “slots” which can store information, precisely seven plus or minus two items. In the view of this theory, if a person tries to remember more than the “limit”, either the accuracy drops, or the information is not remembered at all. In more recent research, Cowan (2001) contends that the limit is lower than what Miller estimated, at four items. Furthermore, he argues that time also plays a role in the storing process, suggesting that as more time passes by, the more difficult it will be for the person to recall the items.

Arguably, newer research challenges Millers and Cowan’s theories and offers a different explanation. Ma et al. (2014), managed to find evidence that VWM does not have a maximal number of items that can be remembered, but it has a flexible precision. According to them, people grasp the idea of objects and sceneries as a complex combination of single features such as orientation, size, and colour. As a result, the limited resource model was created, which explains that the limit of the VWM is defined by variable resources that can be allocated to particular objects or features (Yatziv & Kessler, 2018). Thus, the allocation of resources is heavily relying on how complex the item or object is, more exactly, more features lead to a noisier VWM. Additionally, the resource allocation also depends on the targeted item. Therefore, if attention is given to one object in particular, the targeted item will be remembered easily, while the other items will be part of a noisy VWM (Ma et al., 2014).

Hence, recalling power has more explanations. Firstly, if the item’s complexity is low, a high number can be maintained in-store. An object with complicated features, on the other hand, will necessitate more resources, reducing the number of other items that may be remembered (Ragalmuto, 2020). Furthermore, if the individual focuses their attention on a specific object, the number of recalled items will be low, but the targeted object will be remembered in detail (Ma et al., 2014). Furthermore, evidence provided in the paper written by Steinweg (2021), indicates that when more features are available, one's VWM will focus more on difficult objects, trading easier-to-remember items for complex ones.

Although, based on current studies, it may be evident that the emphasis should shift to designing with the new constraints in mind, over the years, multiple papers have recommended or suggested using Miller's magical number of seven plus or minus two in their design (Arfeen, 2012). Katerattanakul and Siau (1999) endorse Miller's concept that this limitation can be bypassed by splitting information into chunks. According to Rogers et al. (2011), a part of the designers build interfaces with a maximum of seven menu options and no more than seven objects on the display. Moreover, there should be no more than seven tabs at the top of the website. But keeping in mind the new research, is it still true? Therefore, this study aims to determine what are the actual cognitive limits in regard to the limited resource model in a web page environment, as the current standard is seven items per display or chunk. The experimental part is based on Change Blindness (CB), where multiple different displays will be presented that may or may not contain feature changes. CB represents the inability of people to detect large changes to visual scenes (Simons & Ambinder, 2005) and has been used widely as a tool to test VWM (Keshvari et al., 2013). By quickly presenting stimuli, humans and non-humans can be easily tested for their capacity to remember objects (Keshvari et al., 2013). Thus, based on the experimental part, the following main research question will be answered: Up to what number of presented items should an individual be exposed to in order to miss a change? Additionally, the subsequent research question will also be answered: Is there any difference between the type of change and the ability of the individual to address the change?

Methods

Participants

A total of 29 participants (MAge = 23.3, Range:18-54, 20 females and 9 males) took part in the study. Nine participants were German, six were Dutch, and fourteen from other nationalities. Participants that did not successfully pass the colour-blindness test were excluded. University of Twente Faculty of Behavioural, Management and Social Sciences ethics committee approved the experiment under the approval code 230639. All participants gave written informed consent.

Materials

To take part in the experiment, the participant had to own one device (such as a laptop or phone) that could run any web platform. The whole experiment was composed through Qualtrics. The stimuli of the task were created in Adobe Illustrator CC 2019 with a resolution of 1920 x 1080 pixels, the exact measures of a webpage.

The stimuli used in the experiment consisted of multiple items that could either be the same or differ either in colour, form, or both dimensions (see Appendix A). The items resembled common website objects, such as search bars, shortcut buttons, main logos, company logos or trademark texts. The colour changes consisted in completely changing the hue and lightly tweaking the saturation. The form changes consisted in changing the shape of the item, such as changing a shortcut button from a circle to a triangle, while maintaining the same area. It must be specified that the icons inside the shortcut buttons did not suffer any changes.

Procedure

The participants were gathered in two ways. Either, by sending a link through social media apps or through the special participant gathering system SONA, which is moderated by the University of Twente.

Once the participant entered the study, it was met with an information page that described what the study is about and its aims. The participant could not advance to the next page if the informed consent ticks were not checked. As the participant got to the next page, they were met with demographic questions such as age, nationality and gender.

Because the experiment entailed a perceiving change in colours, the succeeding slide tested the participant for colour blindness. This was done through the usage of the Ishihara test. If the participants failed the test, colour blindness was added as a limitation.

After all these steps were completed, the actual experiment started. It entailed 240 trials, where a trial consisted of the participant being presented with two displays, a mask with a fixation cross in between and a final question asking if there was any difference between the two displays. In a trial, the stimuli and the mask were shown only for two seconds. Figure 1 entails the visualisation of a trial. The stimuli were designed to resemble a webpage, such as Google. In addition, each stimulus had a different number of items and was randomly presented throughout the trial, to hinder the participant's ability to get used to the stimuli and in turn lower the reliability of the study. Furthermore, when the number of presented items in the stimulus changed, the colour and form of each item also were modified (see Figure 2a and Figure 2b). Moreover, four conditions were present as follows:

1. The first condition was a no-change condition, where the first presented picture of the trial was identical to the second one.
2. The second condition focused on the colour change of an item. Therefore, the second stimulus had one item with a different colour than the stimulus presented before the mask.

3. The third condition entailed changing the form of one item. Hence, the stimulus presented after the mask consisted of an item with a different form compared to the initial stimulus.
4. The fourth condition was a combination of the second and third conditions, where the changed item differed in colour and form.

To be able to have a better and equal distribution of the results, every change condition was presented eight times for every number of items. The no-change condition was presented 24 times, eight times for every condition.

Figure 1

Trial Timeline Visualisation

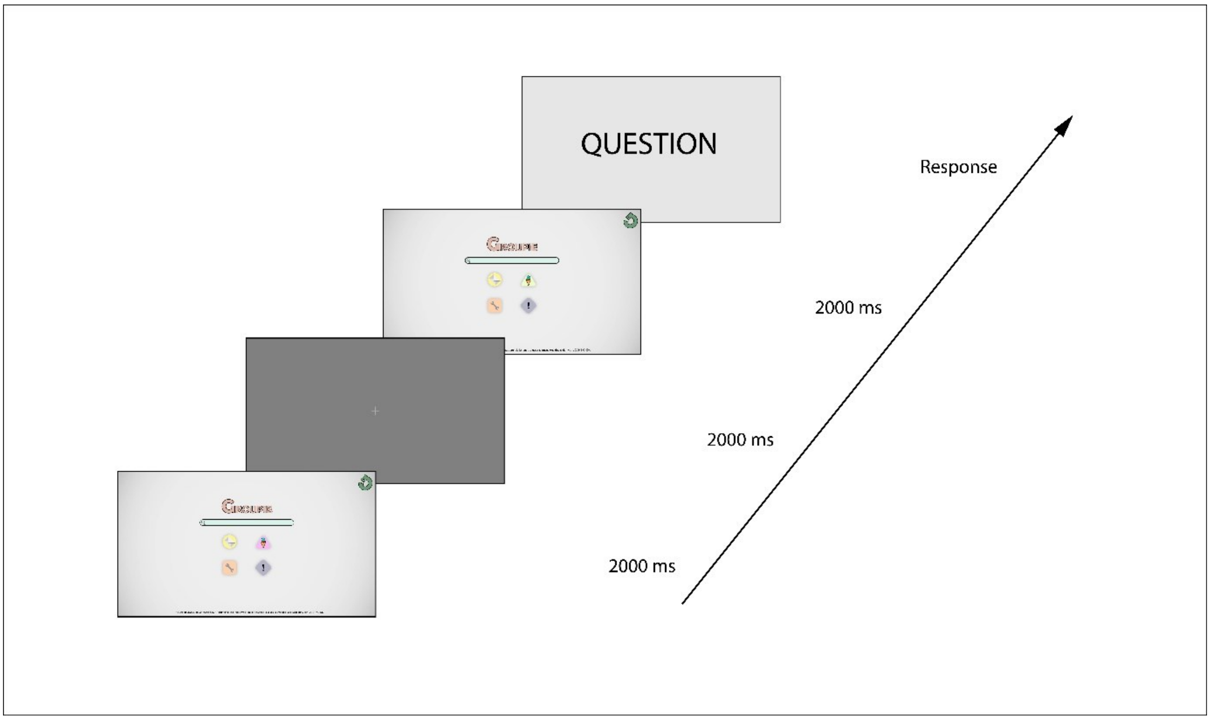


Figure 2a

Display showing 6 items.

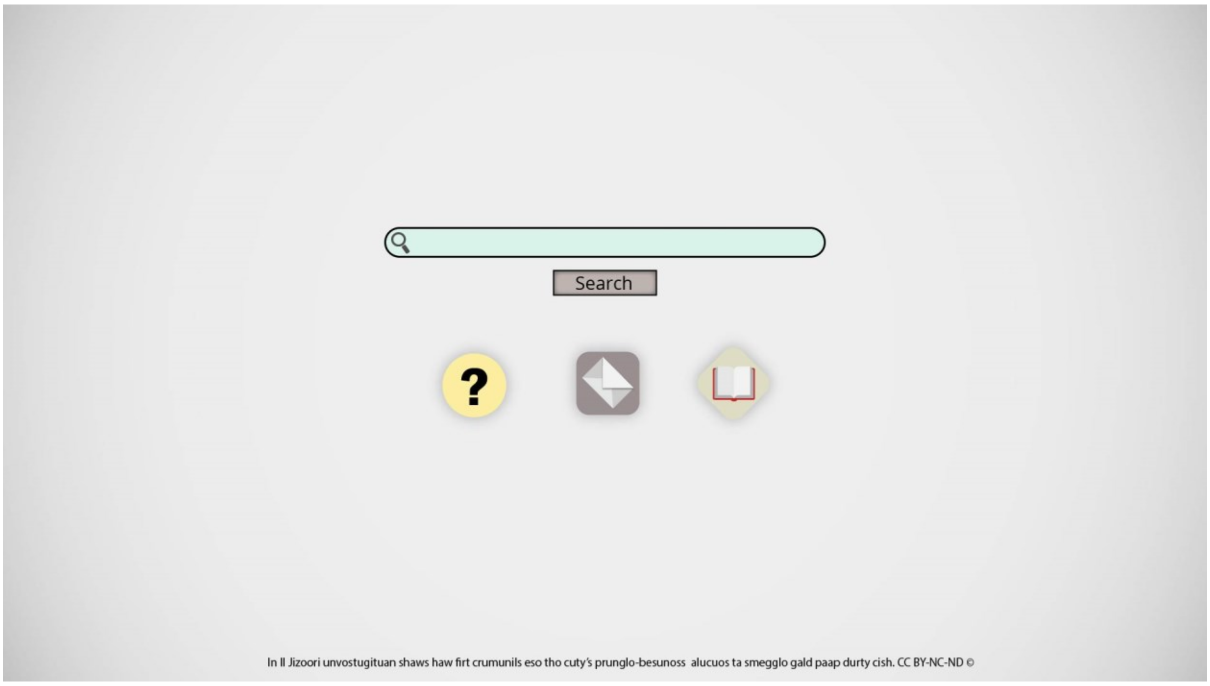


Figure 2b

Display showing 12 items.

Data analysis

In the first phase, d' was calculated for each condition associated with the number of items for each participant. The value was calculated by subtracting the z-score of the False Alarm Rate from the z-score of the Hit Rate. If the Hit Rate or False Alarm Rate were either 1 or 0, Stanislaw and Todorov's (1999) log-linear recommendation was followed. It states that before calculating the hit and false alarm rates, the number of hits and false alarms must be increased by 0.5, and the number of signal trials and noise trials must be extended by 1.

When d' had to be calculated for the various conditions, the absence of False Alarm indicators represented a challenge in the computational process. Therefore, the False Alarm Rate specific to the relevant condition was used. To better illustrate, let us consider the scenario where we need to determine the d' value for the first participant in the colour condition, with four displayed items. While the Hit Rate was calculated in the usual manner, the False Alarm rate was taken from the relevant context, namely, the False Alarm Rate displayed by the first participant in the four-item condition.

The present study evaluated the d' values as indicators of performance, drawing upon Keating's (2005) research as a reference. Keating asserts that a d' value of 4.65 represents the highest level of effectiveness, while an average d' value typically falls around 2. Additionally, Keating notes that a d' value of 1 corresponds to a correct response rate of approximately 69% for both same and different trials. Based on these findings, it was determined that d' values greater than 1.5 would be classified as good, values between 1 and 1.5 as mediocre, and values below 1 as poor.

The following phase involved determining whether the three conditions and the number of items affected the participant's ability to accurately notice a change in the stimuli while comparing the two groups that used different types of devices. To achieve this goal, a three-way mixed ANOVA test was performed with 5 numbers of items (4 items, 6 items, 8 items, 10 items, 12 items) x 3 change conditions (colour, form, colour and form) x 2 the type of device (computer, phone). The device used by participants was a between-groups factor, while changes and the number of items were within-group factors. To check the effect of relevant interactions, a two-way combined ANOVA test was also performed with 5 numbers of items (4 items, 6 items, 8 items, 10 items, 12 items) x 3 change conditions (colour, form, colour and form).

Finally, several t-test contrast analyses were carried out in order to examine each level of the significant factors. The first analysis compared the number of items, including 4 contrast analyses. Similarly, the second contrast analysis contained 10 contrasts comparing the three conditions. The data processing operation was made through Excel version 2303 and RStudio build 386. The RStudio code can be found in the Appendix (see Appendix B).

Results

The impact of the factors on change detection

The study aimed to assess the influence of the number of items in a stimulus (4 items, 6 items, 8 items, 10 items, 12 items), change conditions (colour, form, colour and form), and the type of device used (computer, phone) on participants' ability to detect a change. A 5 (number of items) × 4 (condition) × 2 (device) three-way mixed ANOVA test was conducted to analyse the data (see Table 1). The device factor was between-groups, with the other two being within-group. The results indicated that the number of items had a significant effect on change detection, $F(4, 108) = 15.7$, $p < 0.001$. Additionally, the change conditions significantly affected change detection, $F(2, 44) = 32.8$, $p < 0.001$. In contrast, the type of device did not have a significant effect on change detection, $F(1, 27) = 0.8$, $p = 0.372$. The analysis also checked for interactions and yielded the interaction between change condition and the number of items as the only significant interaction $F(8, 216) = 4.7$, $p<0.001$. Therefore, the findings suggest that only the number of items, change conditions, and the interaction between the two represent significant factors in participants' ability to detect changes in stimuli.

As only the interaction between the condition and items factor was significant, to better analyse the interaction, a combined two-way ANOVA test was performed. The results showed that the interaction effect is not significant $F(8,420) = 2.3$, $p = 0.019$. Therefore, there was no significant interaction between the number of items and the three conditions.

Table 1

5 x 3 x 2 three-way mixed ANOVA output

Effect	Degrees of Freedom	F-value	p-value
Device	27	0.823	0.372
Condition	44	32.851	> 0.01
Items	108	15.747	> 0.01
Device-Condition Interaction	44	0.589	0.525
Device-Items Interaction	108	0.118	0.976
Condition-Items Interaction	216	4.699	> 0.001
Device-Condition-Items Interaction	216	0.575	0.798

Contrast analysis

To examine the main effects of the factors, a multiple contrast analysis was conducted. The "number of items" factor was subjected to four contrasts, comparing five levels (4 items, 6 items, 8 items, 10 items, and 12 items). Similarly, the "change condition" factor was subjected to ten contrasts, encompassing three conditions (colour, form, and colour and form) for each number of items.

The contrast analysis for the "number of items" factor yielded several significant findings, which are presented in Table 2a. Contrast 1 revealed a medium significant difference; however, Contrast 2 did not reach significance. Furthermore, Contrast 3 demonstrated a medium significant difference in change detection, while Contrast 4 did not show a significant difference.

Turning to the "change condition" factor, ten additional contrast analyses were conducted, encompassing the three conditions (colour change, form change, and colour and form change) for each number of items. The results of these analyses are displayed in Table 2b.

Contrast 1 did not reveal a significant difference between the two levels of the factor. In contrast, Contrast 2 showed a significant difference in change detection. Furthermore, Contrast 3 did not yield a significant difference, indicating a lack of distinction between the two levels of the factor. Conversely, Contrast 4 demonstrated a significant difference.

In addition, Contrast 5 did not display a significant difference between the two conditions. However, Contrast 6 resulted in a significant difference between the two levels. On the other hand, Contrasts 7, 8 and 9 did not reveal a significant difference. In contrast, for Contrast 10, there was a significant difference between the two change levels.

Table 2a

Results of the "number of items" factor contrast analysis

Contrast	Comparison	T-value	p-value
1	4 items vs. 6 items	-3.233	0.001
2	6 items vs. 8 items	-0.702	0.484
3	8 items vs. 10 items	-3.058	0.002
4	10 items vs. 12 items	0.976	0.33

Note. The T-values have 172 degrees of freedom.

Table 2b

Results of the "change condition" factor contrast analysis

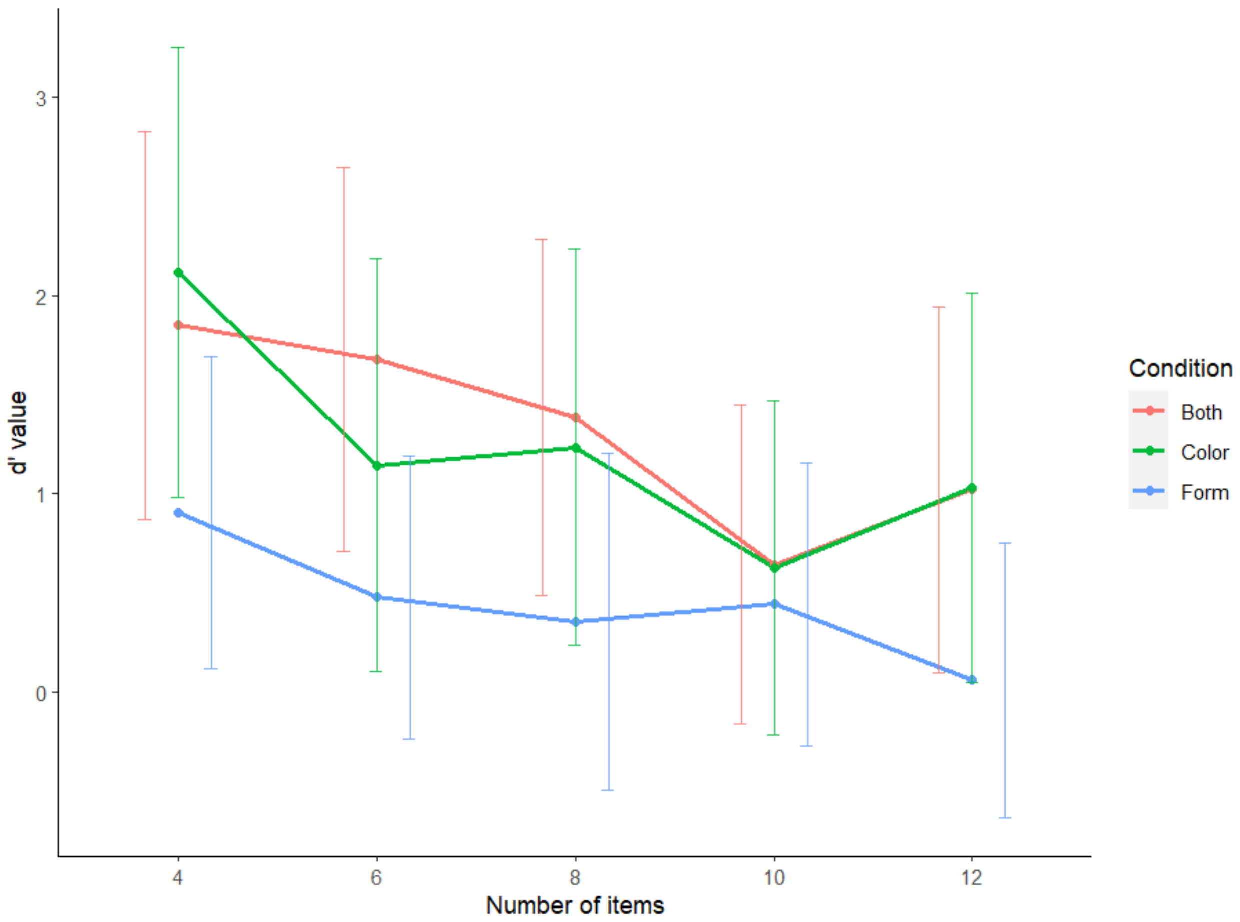
Contrast	Comparison	T-value	p-value
1	Colour vs both (4 items)	-1.044	0.299
2	Colour vs form (4 items)	-4.711	<0.001
3	Colour vs both (6 items)	2.211	0.029
4	Colour vs form (6 items)	-2.766	0.006
5	Colour vs both (8 items)	0.626	0.533
6	Colour vs form (8 items)	-3.666	<0.001
7	Colour vs both (10 items)	0.0072	0.943
8	Colour vs form (10 items)	-0.895	0.373
9	Colour vs both (12 items)	-0.037	0.971
10	Colour vs form (12 items)	-4.224	<0.001

Note. The T-values have 84 degrees of freedom.

Based on the contrast analyses it seemed that the d' value had declined as the number of items increased. Furthermore, the form condition, compared to both and colour conditions, had lower values of d', with the highest being similar in value to the lowest of the two other conditions. For better visualisation, a line plot was computed (see Figure 3). Moreover, the mean error distances decreased slightly as the number of items increased. The form had the smallest error distance mean compared to the other two conditions.

Figure 3

A line plot with error bars



Note. The line plot depicts the variation of d' values as the number of items increases. The lines are divided by condition. The error bars have a small amount of offset to not overlap with each other.

Discussion

This study aimed to investigate the limitations of VWM by examining the impact of three variables on change detection. The research questions focused on the effects of the number of items and the type of feature change on individuals' ability to detect changes.

Concerning the main research question, the analysis of the results revealed a difference in a person's ability to identify a change as the number of objects increased. Participants had greater difficulty detecting changes as the number of items increased. However, even at the highest number of items, the detection rate remained between average values depending on the context, with colour and both changes being above the value of 1. Further analysis of the contrast results indicated that the ability to detect changes remained relatively high for the colour and colour and form conditions, even for high numbers of items, while the form condition showed a significantly lower detection capacity. These findings address the first research question and challenge the limits suggested by Miller (1956) and Cowan (2001), which proposed that individuals can remember only four and seven items, respectively. Additionally, these findings align with the research conducted by Ma et al. (2022), which demonstrated that change detection decreases as the number of items increases.

When focusing on the subsequent research question, the analysis revealed differences in change detection based on the type of change. The results compiled evidence to show that the form feature is the most difficult one to remember, compared to colour and form and colour features. Specifically, the colour condition and colour and form condition consistently yielded similar detection performance, while the form condition showed significantly lower performance in most cases. These results are in line with Steinweg's (2021) study, which found that form features are the most difficult to remember, in contrast to colour. Additionally, the results confirm the findings of Wang et al. (2017), that the load on one feature does not affect the memory performance on other features, as colour and form were very similar in performance with colour change only.

According to the statistical tests that were computed, the type of display was not significantly affecting the ability to detect changes. This could be as the display resolution, although smaller, is closer to the field of view of the individual, hence the lack of difference between the two. Therefore, the difference not being big enough to become significant.

Limitations and future research

Based on feedback, but also on metric data, the experiment was deemed too long. According to the initial calculations, the experiment should have lasted roughly 30 minutes, with each trial lasting 8 to 10 seconds. However, in practice, the majority of participants finished the entire setup in about 50 minutes, and some even abandoned the experiment and came back at a later time, either hours or days later.

Moreover, the capacity of detecting changes in colour could be more heightened than changing the form. Colour changes consisted mainly in considerably changing the hue, which is much more noticeable than changing a square into a triangle. As this study did not contain a pre-test, it is not known what the best form and colour changes are and could serve as material for future studies.

Lastly, it was mentioned by the participants that the experiment lacked display diversity. Trials were fairly identical to one other, and after completing 50 minutes of the experiment, the participants lost interest. It could be argued that users when revisiting a website should experience the same effect. But compared to normal users, the participants of the study did not have an interactive purpose. When exploring a website, such as Google, through interactive usage, it may be that one remembers easily the content of the page, but when told to remember without actively interacting with the display, interest may lower significantly. As a result, the stimuli should either present more diversity and vary in the display design or create an interactive study to not negatively affect reliability.

Thus, for future website developments, designers should keep in mind that form features are complex and will lower the ability to remember many items. As outlined by Steinweg (2021), people have more difficulties remembering complex features such as the form of an object. Colour has an advantage over form, and it should be preferred most of the time if possible. Therefore, if one would like to convey a change in the display, the colour would be the perfect modality for doing it. However, if a website consists of a few items, the complexity of objects can be higher, as a low number of complex items can still be remembered, although not as consistent. But once the number of items increases, one should trade form features for colour or a combination of both.

Thus, new guidelines should be enforced, as previous recommendations mentioned the usage of a maximum of seven items per display, but it was shown that the value could differ and be influenced by many factors. Therefore, the new guidelines based on the findings of this paper are as follows:

- Using forms to transmit information should be done when 4 or fewer items are present.
- Colour should be used confidently for up to four items for information transfer, but when the number of items is higher than 4, one should remember that the quality lowers, although remaining reliable, and should be careful. For higher numbers, the designer could run trial tests.
- The combination of both can be used confidently for up to 8 items, but when the number of items is higher than 8, one should remember that the quality

lowers, although remaining reliable, and should be careful. For higher numbers, the designer could run trial tests.

Conclusion

The current study examined the limits of VWM through the impact of three variables on the ability to detect changes. The answer to the research questions supports the limited resource model that VWM has a flexible precision and contradicts Cowan's (2001) and Miller's (1956) limits. Furthermore, the study supports the idea that individuals can go above the previously imposed limits and remember as many as 12 items if the complexity is low, reinforcing the idea that people use feature recognition, not object recognition. Additionally, the study highlights the differences in change detection based on the type of change, with the form being the most challenging to remember compared to colour and colour and form features. Lastly, recommendations for interface designers are given.

References

Arfeen, M. I. (2012). Assessment of websites: A Case Study of Federal Ministry of Science and Technology. *Life Sci J*, *9*(3), 406.

Bednarz, A. (2019, August 5). *Evolution of the internet: Celebrating 50 years since Arpanet*. Network World. https://www.networkworld.com/article/3410588/evolution-of-the-internet-celebrating-50-years-since-arpanet.html#slide2

Council, N. R., Board, C. S. a. T., & History, C. O. I. I. C. a. C. L. F. (1999). Development of the Internet and the World Wide Web. In *Funding a Revolution* (pp. 169–182). National Academies Press. https://doi.org/10.17226/6323

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24*(1), 87-114. doi:10.1017/s0140525x01003922

Flavián, C., Gurrea, R., & Orús, C. (2009). Web design: a key factor for the website success. *Journal of Systems and Information Technology*, *11*(2), 168–184. https://doi.org/10.1108/13287260910955129

Katerattanakul, P., & Siau, K. (1999). Measuring information quality of web sites: development of an instrument. In *International Conference on Information Systems* (pp. 279–285). https://doi.org/10.5555/352925.352951

Keating, P. (2005). *D-prime (signal detection) analysis*. http://phonetics.linguistics.ucla.edu/facilities/statistics/dprime.htm#:~:text=The%20highest%20possible%20d'%20(greatest,corresponds%20to%20a%20d'%20of%201.0

Keshvari, S., Van Den Berg, R., & Ji, W. (2013). No Evidence for an Item Limit in Change Detection. *PLOS Computational Biology*, *9*(2), e1002927. https://doi.org/10.1371/journal.pcbi.1002927

Ma, C., Wang, H., & Xue, C. (2022). Research on the Relationship Between the Aesthetics of Interface Elements Layout and Visual Working Memory. In *Springer eBooks* (pp. 597–607). https://doi.org/10.1007/978-3-031-17615-9_42

Ma, W. J., Husain, M., & Bays, P. M. (2014). Changing concepts of working memory. *Nature Neuroscience, 17*(3), 347-356. doi:10.1038/nn.3655

Mannix, K., & Hall, S. (2017, April 12). The evolution of the internet. *The Telegraph*. https://www.telegraph.co.uk/technology/0/evolution-internet/

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *63*, 81-97. doi:10.1037/h0043158

Peterson, D. J., & Berryhill, M. E. (2013). The Gestalt principle of similarity benefits visual working memory. *Psychonomic Bulletin & Review*, *20*(6), 1282–1289. https://doi.org/10.3758/s13423-013-0460-x

Ragalmuto, F. (2020). *Visual Working Memory for Sizes and Orientations* [BA thesis]. University Of Twente.

Renner, V. (2022). *Precision of Visual Working Memory: How Colours and Sizes Decay over Time* [BA thesis]. University of Twente.

Rogers, Y., Sharp, H. L., & Preece, J. (2011). Interaction Design: Beyond Human-Computer Interaction. In *John Wiley eBooks*. http://discovery.ucl.ac.uk/1326236/

Simons, D. J., & Ambinder, M. S. (2005). Change Blindness. *Current Directions in Psychological Science*, *14*(1), 44–48. https://doi.org/10.1111/j.0963-7214.2005.00332.x

Stanislaw, H., & Todorov, N. (1999). Calculation of signal detection theory measures. *Behavior Research Methods Instruments & Computers*, *31*(1), 137–149. https://doi.org/10.3758/bf03207704

Steinweg, I. (2021). *Flexible Resources in Visual Working Memory for Color, Size, and Orientation* [BA thesis]. University of Twente.

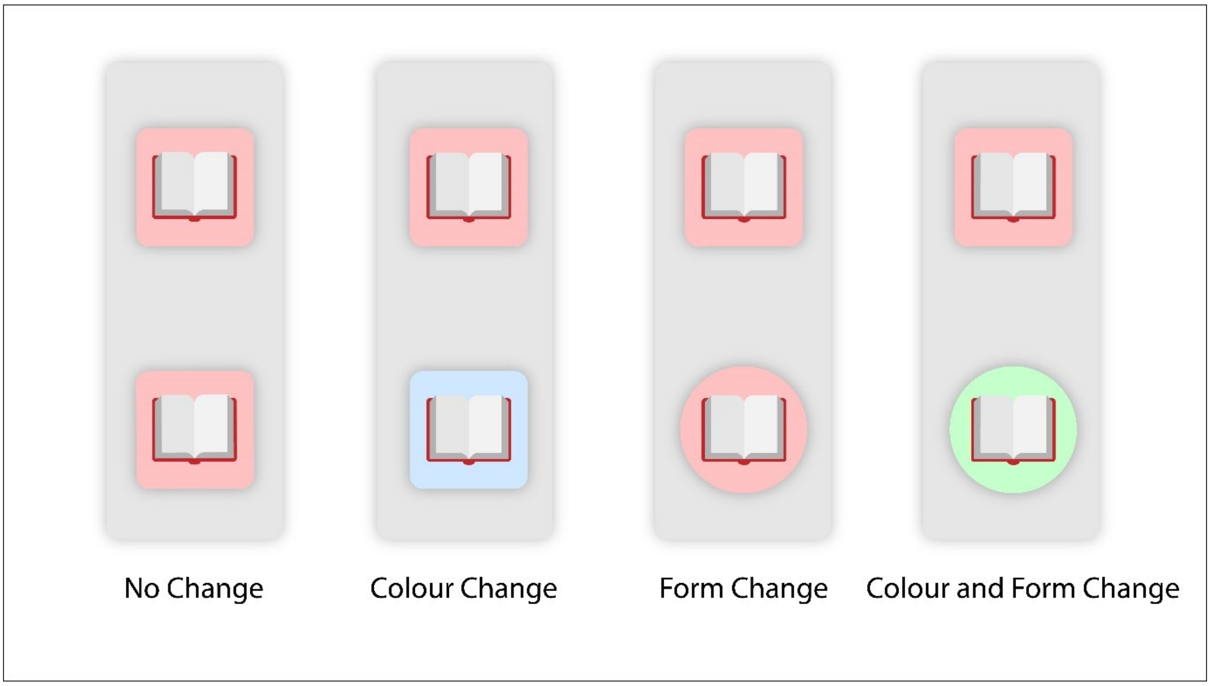
Wang, B., Cao, X., Theeuwes, J., Olivers, C. N., & Wang, Z. (2017). Separate capacities for storing different features in visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 43*, 226-236. doi:10.1037/xlm0000295

Yatziv, T., & Kessler, Y. (2018). A two-level hierarchical framework of visual short-term memory. *Journal of Vision, 18*(9), 1-26. doi:10.1167/18.9.2

Appendices

Appendix A

The different change conditions of items



Appendix B

RStudio Code

```
library(tidyverse)

library(data.table)

library(readxl)

library(psycho)

library(ggplot2)

library(ggpubr)
```

```
library(broom)

library(AICcmodavg)

library(stats)

library(rstatix)



df <- read_excel("/path_to_file")



df$ID <- as.factor(df$ID)

df$Condition <- as.factor(df$Condition)

df$Items <- as.factor(df$Items)

df$Device <- as.factor(df$Device)



#Anova within between

res.aov <- anova_test(

  data = df, dv = Dprime, wid = ID,

  between = Device, within = c(Condition, Items)

)

get_anova_table(res.aov)

##

#omnibus
```

```
anova(lm(Dprime ~ Condition * Items, df))

##

# contrast analysis 4-6 items & interaction

fsixitems <- read_excel("/path_to_file ")

fsixitems$ID <- as.factor(fsixitems$ID)

fsixitems$Condition <- as.factor(fsixitems$Condition)

fsixitems$Items <- as.factor(fsixitems$Items)

fsixitems$Device <- as.factor(fsixitems$Device)


summary(lm(Dprime ~ Items, fsixitems, contrasts = list(Items = contr.treatment(2))))


summary(lm(Dprime ~ Items:Condition, fsixitems, contrasts = list(Items = contr.treatment(2),
        Condition = contr.treatment(3))))


# contrast analysis 6-8 items & interaction


seitems <- read_excel("/path_to_file ")

seitems$ID <- as.factor(seitems$ID)

seitems$Condition <- as.factor(seitems$Condition)

seitems$Items <- as.factor(seitems$Items)
```

```
seitems$Device <- as.factor(seitems$Device)


summary(lm(Dprime ~ Items, seitems, contrasts = list(Items = contr.treatment(2))))


summary(lm(Dprime ~ Items:Condition, seitems, contrasts = list(Items = contr.treatment(2),
        Condition = contr.treatment(3))))

# contrast analysis 8-10 items & interaction


etitems <- read_excel("/path_to_file ")

etitems$ID <- as.factor(etitems$ID)

etitems$Condition <- as.factor(etitems$Condition)

etitems$Items <- as.factor(etitems$Items)

etitems$Device <- as.factor(etitems$Device)


etitems <- etitems %>%

  mutate(Items = relevel (Items, ref = "8 items"))


summary(lm(Dprime ~ Items, etitems, contrasts = list(Items = contr.treatment(2))))
```

```
summary(lm(Dprime ~ Items:Condition, etitems, contrasts = list(Items = contr.treatment(2),
        Condition = contr.treatment(3))))

# contrast analysis 10-12 items & interaction


ttitems <- read_excel("/path_to_file ")


ttitems$ID <- as.factor(ttitems$ID)

ttitems$Condition <- as.factor(ttitems$Condition)

ttitems$Items <- as.factor(ttitems$Items)

ttitems$Device <- as.factor(ttitems$Device)


summary(lm(Dprime ~ Items, ttitems, contrasts = list(Items = contr.treatment(2))))


summary(lm(Dprime ~ Items:Condition, ttitems, contrasts = list(Items = contr.treatment(2),
        Condition = contr.treatment(3))))

##

#contrast analysis 4 items condition


fcond <- read_excel("/path_to_file ")
```

```
fcond$ID <- as.factor(fcond$ID)

fcond$Condition <- as.factor(fcond$Condition)

fcond$Items <- as.factor(fcond$Items)

fcond$Device <- as.factor(fcond$Device)



fcond <- fcond %>%

  mutate(Condition = relevel (Condition, ref = "Color"))



summary(lm(Dprime ~ Condition, fcond, contrasts = list(Condition = contr.treatment(3)))).



#contrast analysis 6 items condition

scond <- read_excel("/path_to_file ")

scond$ID <- as.factor(scond$ID)

scond$Condition <- as.factor(scond$Condition)

scond$Items <- as.factor(scond$Items)

scond$Device <- as.factor(scond$Device)



scond <- scond %>%

  mutate(Condition = relevel (Condition, ref = "Color"))
```

```
summary(lm(Dprime ~ Condition, scond, contrasts = list(Condition = contr.treatment(3))))

#contrast analysis 8 items condition



econd <- read_excel("/path_to_file ")



econd$ID <- as.factor(econd$ID)

econd$Condition <- as.factor(econd$Condition)

econd$Items <- as.factor(econd$Items)

econd$Device <- as.factor(econd$Device)



econd <- econd %>%

  mutate(Condition = relevel (Condition, ref = "Color"))

summary(lm(Dprime ~ Condition, econd, contrasts = list(Condition = contr.treatment(3))))



#contrast analysis 10 items condition



tecond <- read_excel("/path_to_file ")

tecond$ID <- as.factor(tecond$ID)

tecond$Condition <- as.factor(tecond$Condition)

tecond$Items <- as.factor(tecond$Items)
```

```
tecond$Device <- as.factor(tecond$Device)

tecond <- tecond %>%

  mutate(Condition = relevel (Condition, ref = "Color"))

summary(lm(Dprime ~ Condition, tecond, contrasts = list(Condition = contr.treatment(3))))

#contrast analysis 12 items condition

twcond <- read_excel("/path_to_file ")

twcond$ID <- as.factor(twcond$ID)

twcond$Condition <- as.factor(twcond$Condition)

twcond$Items <- as.factor(twcond$Items)

twcond$Device <- as.factor(twcond$Device)

twcond <- twcond %>%

  mutate(Condition = relevel (Condition, ref = "Color"))

summary(lm(Dprime ~ Condition, twcond, contrasts = list(Condition = contr.treatment(3))))



#geomline

gl <- read_excel("/path_to_file ")

gl$Condition <- as.factor( gl$Condition )



ggplot(data = gl, aes(x = Items, y = Dprime, color = Condition)) +

  geom_line(aes(group = Condition), size = 1.1) +
```

```
  geom_point() +
  geom_errorbar(aes(ymax = Dprime + SD, ymin = Dprime - SD),
                width = 0.2,
                position = position_dodge(width = 0.5),
                alpha = 0.8) +
  labs(x = "Number of items", y = "d' value") +
  theme(panel.grid.major = element_blank(),
        panel.grid.minor = element_blank(),
        panel.border = element_blank(),
        panel.background = element_blank(),
        axis.line = element_line(colour = "black"))


gl$Items <- factor(gl$Items, levels = c("4", "6", "8", "10", "12"))


####
```