

COLOR MEMORY DIFFERENTIATION AS AN ADAPTIVE
REMEDY FOR HIGHLY SIMILAR OBJECT MEMORIES

by

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A THESIS

Presented to the Department of Psychology
and the Robert D. Clark Honors College
in partial fulfillment of the requirements for the degree of
Bachelor of Science

June 2020

An Abstract of the Thesis of

Ania Grudzien for the degree of Bachelor of Science
in the Department of Psychology to be taken June 2020

Title: Color memory differentiation as an adaptive remedy for highly similar object memories

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Potential for memory confusion occurs when remembering highly similar objects encountered within the same context. Memory differentiation, an adaptive mechanism by which the brain distinguishes memories that share a high degree of representational overlap, emerges as a potential brain remedy. Differentiation can be understood as the ability to manipulate highly similar memories by exaggerating the differences between them in order to keep them distinct in mind. In this experiment, we examined differentiation of color memory in a visual spatial context. We employed a behavioral memory experiment, with computer generated colored object stimuli, operationalized as a color and location memory task. Students from the University of Oregon Human Subjects Pool were asked to memorize the spatial locations of colored object pairs. The colored objects were partitioned into two groups, a paired group (identical objects, highly similar in color), analogous to memories with a high degree of representational overlap, and a control group (different objects, highly similar in color), analogous to unique memories. A two-way ANOVA comparing color differentiation for object group and object location yielded a marginally significant effect of object group,

such that subjects exhibited a greater degree of differentiation for highly similar paired objects. In addition, we found a significant, negative linear relationship between errors in location memory and degree of color differentiation. The results lend support to previous research suggesting a high degree of representational overlap leads to memory differentiation in order to prevent errors and confusion in human memory.

Acknowledgements

First, I would like to thank my primary thesis advisor Dr. Brice Kuhl for continuously supporting and mentoring my project, for opening the opportunity to explore research under the guidance of his wonderful lab, and for providing me the resources, thanks to which I was able collect all of my data before the COVID-19 shut down. I extend my thanks to Dr. Nicole Dudukovic, my Honors College Representative, for providing wise words of advice and providing new insights along my thesis discovery path. It wouldn't be possible without her guiding words. Special thanks from the bottom of my heart, to PhD student Yufei Zhao for graciously mentoring me every step of the way from learning how to design a study, to acquiring the programming tools to tell the story of my data, to reviewing my thesis drafts as they came. A warm expression of gratitude to my Thesis Prospectus professor Dr. David Frank for inspiring me to frame my thesis as a story that will speak to everyone's mind. Lastly, this would not be possible without the loving support of my family, who helped draw new conclusions from this research, who encourage me to be ever curious, and who help me express gratitude in all experiences and have faith through all challenges.

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Introduction

Imagine the following, all too familiar scenario: an eye witness misidentification due to a memory distortion, which results in the conviction of an innocent suspect. Now, enter the real culprit... the hippocampus. The hippocampus is a region of the brain that has evolved over the past thousands of years and is implicated in cognitive processes including learning, memory, and spatial navigation. Now before you convict this newfound culprit, I suggest you wait. Recent research suggests that the hippocampus is involved in an adaptive form of memory distortion referred to as “memory differentiation,” which can be understood as the brain’s innate ability to manipulate memories that are highly similar and exaggerate the differences between them in order to keep them distinct in mind (Duncan & Schlichting, 2018). This process ultimately results in distorted memories. In our court scenario, two faces in the lineup happened to be very similar. In order to distinguish them, the hippocampus exaggerated the eyewitnesses’ memory in favor of one face, resulting in the misidentification. Thus, depending on the context, differentiation can be a help or a hindrance.

This investigation will explore hippocampal color differentiation in the context of visual spatial memory via a behavioral perspective. When two objects are highly similar and are encountered in the same context, this creates potential for confusion. Take the example of pulling into your employer’s parking lot and encountering your coworkers silver Kia Soul parked where you normally park your silver Toyota Scion xB. You decide to park close by. Now imagine returning to your car after a long day of work, clicking the unlock button and pulling on the door handle, only to discover that this was, in fact, your coworkers Kia. Instead of cars, in our experiment we tasked

participants with memorizing the locations of colored objects. In addition, we asked them to recall the correct color of any prompted object. We hypothesized that the color memory feature would be misremembered for two objects that are highly similar in color. If color memory features are misremembered such that the differences between similar memories are exaggerated, this would suggest evidence of behavioral differentiation. While behavioral methods do not allow us to identify and outline specific neurological mechanisms underlying a psychological phenomenon, the patterns the behavioral results reveal can provide convincing evidence for further investigation with the use of fMRI research methods.

With the aim of elucidating the process of hippocampal differentiation, not only do we examine whether something was misremembered, but we ask the fundamental question *why*. In particular, we pose the following questions: does differentiation apply to color memory when a visual spatial element is introduced? Can we observe this process behaviorally, or in other words, will participants exaggerate the color of two highly similar objects? Based on our observations of participants' behavior in the context of visual spatial memory, can we conclude that the process of differentiation helps prevent memory errors and thus, confusion? Applying this to our car example, maybe your embarrassing mistake of almost unlocking your coworker's vehicle, could have been prevented if your brain exaggerated the subtle color difference of the two cars.

The results of this investigation build on an existing body of knowledge that already suggests the process of differentiation applies to other cognitive contexts. A perusal of the literature suggests that these include memory in the context of spatial

navigation tasks, visual working memory in the context of stimuli discrimination, as well as memory encoding across time (temporal memory). More broadly, the results of this project will allow us to re-conceptualize and re-evaluate the way we think about memory distortions; unlike in the eyewitness misidentification scenario, in some contexts, distortion is a solution for an information-retrieval problem the memory system faces. No longer will we think of false memories as a consequence of memory's faulty and inaccurate nature. In the process of asking *why* something was misremembered, we come to a greater understanding of the purpose of distorted memories, realizing that they are in fact a gift in disguise, as they enable us to avoid confusion.

Background

Although memory distortion results in false memories, this processes is adaptive and contributes to efficient and flexible memory functioning. Schacter, Guerin, and Jacques (2011) illustrate this in a systematic review of three types of identified memory distortions including imagination inflation, post-event misinformation, and gist-based and associative memory errors. The imagination inflation theory states that memories can be altered based on imagining a false event. This provides for memory's great flexibility to integrate additional information, all at the cost of its accuracy. Associative and gist-based memory errors are errors in memory that occur due to priming individuals to recognize unknown stimuli and memories. For example, seeing the word pillow in a word line-up makes you think of sleep, and later you report reading the word sleep in the lineup, when in fact, it was not included. Post-event misinformation refers to the ability of the mind to integrate information after an event has occurred, to the

degree that the individual truly believes it occurred. This type of error reflects the power of social conformity, and the brain's ability to incorporate new information to constantly update. The above examples illustrate the unique flexibility of memory and the brain's potential to modify memories. We suggest that hippocampal differentiation is another example that belongs in the mix.

In order to investigate how memories are modified, we must understand what contributes to their inherent flexibility. Throughout the ages, philosophers and scientists have suggested various metaphors to describe memory including, memory as a process, a storehouse, and memory as a representation. The latter suggests that memories are shaped by their representations; the pattern of neural activity that codes for a memory and allows active recall (Duncan & Schlichting, 2018). The process of differentiation, our topic of interest, actively repels representations that share a high degree of neural overlap, in comparison to those that do not. This is selective, such that the memory features of highly similar memories are further distinguished (exaggerated) compared to two non-related memories. In order for this phenomenon to occur, there must be opportunity for modifying the memory representations: these may include reactivation of the memory, misprediction (i.e. weakening of an activated memory due to a new context), and re-studying the to-be-remembered item.

Imaging Studies

Practically speaking, how does differentiation occur? It occurs through learning. Learning is an essential mechanism in driving apart internal representations of highly similar memories. Hulbert and Norman (2014) conducted an fMRI analysis to investigate the role of the hippocampus in differentiation to test if neural differentiation

led to a reduction in competition between highly similar stimuli (memories). Every time a memory is retrieved, it is strengthened. This sometimes occurs at the peril of other, competing memories, as these memories are weakened. We refer to this phenomenon as retrieval-induced forgetting. We refer to memory improvement that allows one to retrieve those competing memories as “reverse” retrieval-induced forgetting. The researchers believed differentiation had a role to play by relating neural differentiation to differences in individual reverse retrieval induced forgetting. If this process was indeed due to the effect of neural differentiation, then higher differentiation levels would be correlated to higher levels of forgetting, which is what Hulbert and Norman (2014) found. They found that the degree of neural differentiation was related to and predicted by the left hippocampus. These results point to the fact that the hippocampus is intimately involved in the process of neural differentiation, and that retrieval drives this process. Thus, with increased learning opportunities, highly similar memories are differentiated.

Favila, Chanales, and Kuhl (2015) also employed neuroimaging techniques, and came to a similar conclusion. Their results suggest that learning leads to differentiation, which ultimately prevents interference between highly similar memories. Ultimately, learning drove highly similar paired memories away from each other (i.e. repulsion) in representational space. With learning, the clustering of overlapping representations was eliminated, fleshed out, until each memory was unique and fully differentiated. Favila et al. suggest that differentiation is driven by representational competition between two overlapping memory representations. This led to the further conclusion that overlap of hippocampal representations is the primary cause of memory interference. Thus, the

degree of memory representation similarity seems to be a driving factor for the differentiation process.

Inspired by Kyle, Stokes, Leiberman, Hassan and Ekstrom (2015), who discovered that neural codes for similar spatial environments have significant overlap and must be separated in order to yield successful discrimination, Chanales, Oza, Favila and Kuhl (2017) uncovered additional aspects of the differentiation process. Chanales et al. employed a real world route learning paradigm which contained pairs of highly similar overlapping routes and non-overlapping routes. First, Chanales et al. discovered that learning facilitated the gradual diversion of highly similar neural representations to the point that they differed more than representations of non-overlapping events. In other words, results showed representational repulsion during parts of the route that overlapped. This phenomenon was absent for non-overlapping events. This all suggests that the hippocampus is instrumental in separating neural representations in the context of spatial navigation. These findings provide another dimension to our understanding of this higher order cognitive process; highly similar memories in the context of spatial navigation also differentiate.

Non-human Animal Studies

Two animal studies suggest that differentiation is a global phenomenon, occurring in both human and non-human animals. Bretas et al. (2019) conducted an animal study in which they recorded monkey neuronal activity while the monkeys performed a spatial navigation paradigm with an additional reward factor. Researcher's monitored reward-related neurons as well as place-dependent neurons. They found evidence of neural differentiation, such that segments of overlapping routes were

distinctly coded (compared to non-overlapping routes) in both place-dependent and reward-related neurons. The overlapping routes associated with reward were even less susceptible to overlap, suggesting reward and motivation enhance differentiation. Agster, Fortin, and Eichenbaum (2002) performed a study on mice, testing the animals' ability to distinguish ambiguous odor choices. Mice with functioning hippocampi successfully disambiguated all odor choices. However, mice with hippocampal lesions lost the ability to distinguish overlapping odor stimuli. These results provide more evidence that suggest differentiation occurs on the micro (neural) level and macro (hippocampal) level. The hippocampus is important in differentiating highly similar memories, across many stimuli contexts and animal species.

Visual-Spatial and Color Differentiation

Research investigating the phenomenon of visual working memory (WM) employed similar experimental paradigms as we employed in the current investigation. Bae and Luck (2017) investigated the long-held hypothesis that memory representations of different objects are encoded independently in WM. Bae and Luck (2017) suspected the opposite; that WM representations are coded relationally, i.e. in the context of other memories. In the first version of their experiment, researchers tasked participants with memorizing teardrop shaped stimuli at different orientations on a 360 degree circle. Bae and Luck (2017) found that when the memories were highly similar (less than 90 degrees apart) participants overestimated the orientation of the target stimulus. This is evidence of repulsion of representations. Conversely, when the memories were dissimilar (more than 90 degrees apart) the reported orientation was biased towards the target, providing evidence of attraction. This experiment implies that differentiation is

context dependent; WM representations interact with each other based on their degree of similarity. After all, “context is everything.” These results are particularly informative, as they suggest that differentiation occurs based on some quantifiable threshold level of similarity.

In a second version of the experiment, Bae and Luck (2017) wanted to investigate whether attentional priority had a mitigating effect on the interaction of representations. The key finding was that the repulsion/attraction phenomena were less apparent for stimulus targets for which participants were asked to specifically attend to before encoding (pre-cuing). This suggests that increased attention may aid in protecting the fidelity of representations by increasing their stability. Additionally, researchers suggest that cuing attentional priority after the memories have been encoded (post-cuing) also protects the fidelity of said representation. This suggests that differentiation cannot only be explained by perception of stimulus. Increasing the priority of a memory representation even when there is no opportunity for attention to impact encoding, can protect memory from modification. Consequently, another layer of this complex process is illuminated; attention modulates the degree to which memories differentiate.

In the same context of visual WM, Rademaker, Bloem, Weerd, and Sack (2015) investigated the influence of distractor stimuli and their effect on biasing visual working memory representations of orientation of Gabor patch stimuli. Gabor patches are images of black and white bars of different orientations, thickness, and abundance. Critically, researchers showed that memory for spatial orientation is prone to memory distortion, such that larger differences between target and distractor orientations led to a

bias of orientation toward the distractor, indicating an integration of representations. This was not the case when the target and distractor had a higher degree of orientation similarity, leading to the conclusion that memory varied as a function of target-distractor difference. Interestingly, this attraction effect diminished when the distractor was made “task relevant.” Pertaining to these findings, researchers propose that WM biases could be decisional, rather than perceptual in nature, in harmony with the findings of Bae and Luck (2017). In other words, we make decisions (either consciously or not) which allow us to derive meaning from quantifiable differences. Depending on the degree of these quantifiable differences, we can apply a mental operation in order to differentiate and simplify. In this way, differentiation is a cognitive mechanism which allows us to ascribe meaning to the world around us.

One of the ways we ascribe meaning to the world is with color. Most recently, Chanales, Tremblay-McGaw, and Kuhl (in review) showed evidence of differentiation in color memory. Researchers engaged participants in an associative learning task where participants learned object-face pairs. Each object was paired with two different faces, and the hues of the object pairs were manipulated to have low, moderate, and high similarity. Critically, the researchers found a strong repulsion effect for the high similarity condition such that reports of color memory were biased away from the competing object. Importantly, the results suggested that color memory repulsion is adaptive. Subjects made fewer swap errors (i.e. confusing face-object pairs) when the repulsion effect was present and biased away from the competitor. These findings suggest that differentiation for color memory allows us to create mental contrast, with the goal of eliminating confusion.

Chanales et al. (in review) demonstrated differentiation in the context of associative color memory. Bae and Luck (2017) demonstrated visual spatial differentiation. We aim to investigate these two phenomena jointly. We investigate whether or not the addition of a visual-spatial context will change or interact with the effect of color differentiation already demonstrated by Chanales et al. (in review). Specifically, we examine whether participants differentiate their color memory for two highly similar objects that are close together in visual space. We hypothesize that the repulsion effect will generalize to color memory in a visual spatial context. We expect to observe behavioral evidence of differentiation, such that participants will exaggerate the color feature of the visual memory.

In practical terms, participants should exaggerate the difference in color between highly similar pairs only. We expected this effect to be even greater for similar objects that are closer together in space, such that there will be a location-color interaction. We generally expected this effect to be absent in object pairs that are highly dissimilar (baseline conditions), simply because the dissimilar objects do not share a high enough degree of representational overlap to drive competition for the same representational foothold. Hence, repulsion should be driven by a high degree of similarity and will be competition dependent. For this result to be meaningful, we expect the exaggeration in the highly similar memory condition to be markedly greater than at baseline conditions, such that we will observe a significant negative correlation. We tentatively propose, that differentiation in the context of visual memory is a symptom of memory distortion carried out by the brain in order to create mental contrast and avoid visual spatial

confusion, suggesting that differentiation in the context of visual spatial memory is also adaptive.

Method

Participants

Participants ($N= 43$) included students from the University of Oregon Human Subjects Pool. In accordance with University of Oregon Institutional Review Board policy, all participants provided consent before participation and disclosing their information. Three subjects were excluded from the final analysis because their location test error score was two or more standard deviations above the mean. The location error score exclusion criteria were associated with final color test mean reaction times of less than 1 second. Our subject population included in the final data analysis ($N= 40$) had an age range of 18 to 25 years of age, ($M= 19.12$, $SD= 1.34$). 33% of subjects identified as male and 67% as female. All subjects reported normal or corrected-to-normal vision.

Materials

The stimuli were composed of everyday objects. Each of the objects contained a centered black dot to help orient their location on the screen. Half of the objects were paired such that they were highly similar “pair mates” meaning they are identical objects, highly similar in color (i.e. 22.5 degrees away on color wheel, analogous of similar memories which share a high degree of representational overlap). See Figure 1 for an illustration of different colored stimuli, where each object is 22.5 degrees away from its neighbor. The other half of the objects were paired to be dissimilar, i.e. *different objects*, highly similar in color (analogous of different memories lacking significant representational overlap). In our experimental design we employed both color manipulation (similar competing pairs referred to as the “paired group” and

dissimilar pairs referred to as the “control group”), and location manipulation (half of the pairs in each group had competing locations with each other on the screen).



Figure 1. Sample object color stimuli

Grouped objects had two distances (measured in pixels). The close condition included objects 90 pixels apart, and the far condition included objects measured 540 pixels apart in either the horizontal or vertical direction. For both the paired and control groups, objects were presented in two orientations; the vertical (y) and the horizontal (x). We collected data on the x and y distance the subject placed the remembered stimulus in relation to the location of the competitor stimulus. Only one dimension was useful in determining if repulsion was observed due to the fact that competing stimuli were oriented to induce competition on one dimension only. Across all pairs, the control group was located 90 degrees away (clockwise) from the corresponding paired group.

Procedure

Participants first completed a 14 round learning task, in which they learned the locations of 16 colored object stimuli. In each round, all 16 objects were shown. This task was completed on a computer screen, in a quiet laboratory testing room. At the

start of each learning round, participants fixated on a fixation cross for 500 ms after which they were presented with the colored object stimuli, one by one, in their unique locations, 3.5 seconds apart in succession. During this presentation, subjects were to sit and observe, and were not required to interact with the computer in any way. After presentation, one of two test phases followed. Subjects were asked to indicate the remembered location of each object as prompted on the computer screen. In other words, participants used the computer mouse to drag a presented object to its correct location. This test was self-paced. Participants were provided with written feedback based on how closely their answer matched the correct location of the target object. The levels of feedback included: excellent (0-30 px away from correct location), good (30-60 px), satisfactory (60-90 px), almost there (90-120 px), and try harder next time (120 px+). In addition to written feedback, participants saw the object at its correct location presented again, for 1.5 seconds. We collected data based on the location (in pixels) of the remembered object in relation to its competitor.

The location test was interleaved with a color test. After a study round in which participants observed the color and location of an object, they were cued with the object in gray scale and were asked to recall its color by turning a color wheel until they reached the remembered object color. This response was self-paced. The answers were recorded as integers (0-359) corresponding to the hue (i.e. degree on the color wheel). In addition to measuring memory for object location and color, we measured reaction time for all responses.

The location test and color test were counterbalanced, as shown in Figure 3. After the first learning round, half of the subjects began the test phase by completing the

location test, followed by another learning round and a color test. Then vice versa; half of the subjects began the test phase after the first learning round by completing the color test, followed by another learning round and a location test. Throughout the data collection process we collected data from both experimental paradigms, such that even numbered participants were assigned to one paradigm, and the odd numbered participants to the other as demonstrated in Figure 3. All subjects completed a second set of memory tests; an eight round final memory test, consisting of four rounds of both the location and color test without learning phases in between. The final tests were also counterbalanced as illustrated in Figure 4, such that half of the subjects completed four rounds of the location test and finished with four rounds of the color test, and vice versa. The goal of the final test was to produce a steady baseline level of memory for location and color to inform the final data analysis.

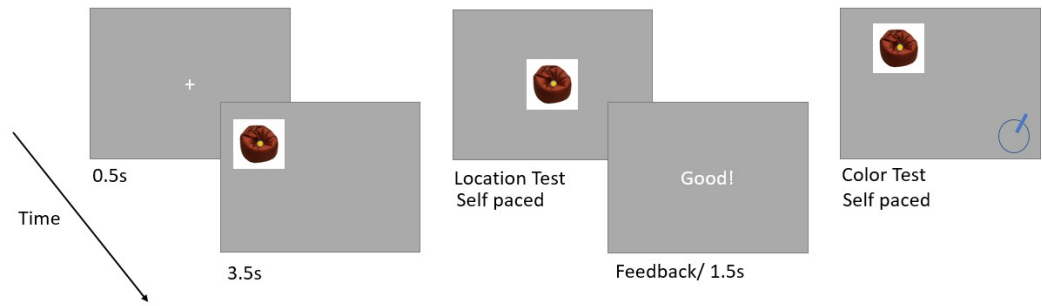


Figure 2. Experimental paradigm showing progression of testing rounds and learning rounds as experienced by participants

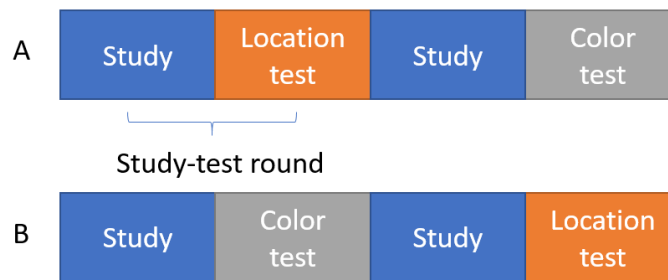


Figure 3. Experimental paradigm for learning phase of experiment

Odd numbered subjects completed 14 study-test rounds of paradigm A, even numbered subjects completed 14 study-test rounds of paradigm B.

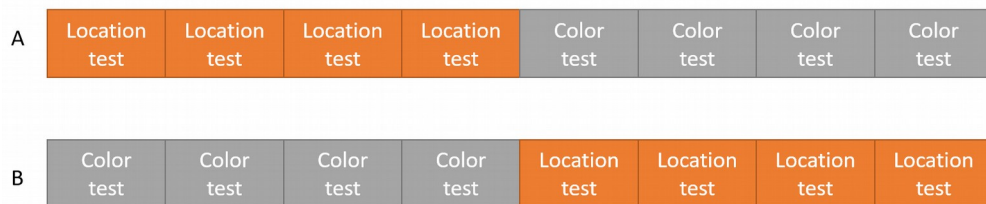


Figure 4. Experimental paradigm for final memory test

Odd numbered subjects completed paradigm A, even subjects completed paradigm B.

Results

Location Memory Performance

As established before by Favila, Chanales, and Kuhl (2015), learning is thought to be a crucial mechanism by which differentiation occurs. To establish whether subjects learned successfully over the series of training rounds, we computed the absolute distance they placed the object from its correct, target location as the index of their location memory performance. This measurement was averaged across participants for each location training round. The exponential decay curve shown in Figure 5, relating learning round number to the average absolute distance from the target location, suggests that rounds participants improved in their location memory with subsequent training.

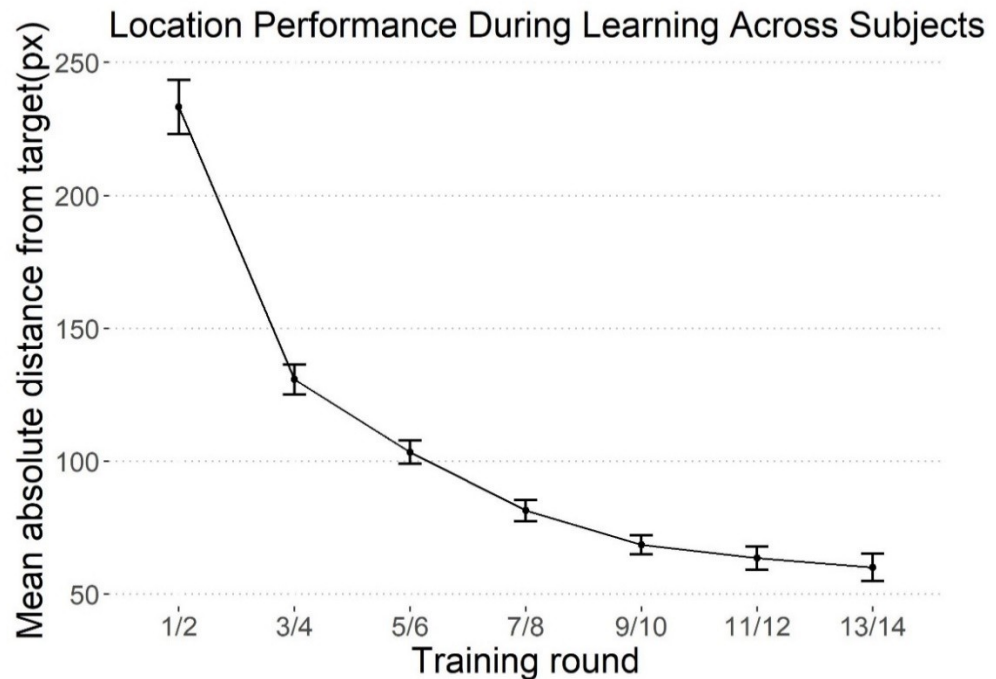


Figure 5. Memory performance on location test during the learning phase
 Memory responses averaged across participants

Color Memory Differentiation: Positive Color Bias

Now that successful learning is established, the primary measures we are interested in are the measures of color repulsion from the final memory test. We assessed participant’s color memory by calculating the location of the target, competitor, and answer choices from an arbitrary zero degree location on the color wheel. Importantly, we investigated a “positive color bias” variable. We designated positive color bias responses by subtracting the participants’ response on the color wheel (degrees) from the correct location of the target on the color wheel. Both locations were measured in reference to the arbitrary zero degrees on the color wheel. If repulsion occurred, meaning that color memory response was biased away from the

competitor, the response was given a positive value, and thus indicated a positive color bias. If attraction toward the competitor was observed, we assigned a negative value to the memory response. Thus, this measure reflects color memory and repulsion in terms of the target object's locations on the color wheel, compared to the competing object's location.

Figure 6 shows the visual representation of this measure. To interpret Figure 6 qualitatively, after averaging color repulsion across subjects and testing rounds, we observed more repulsion for the paired, close condition, such that when objects were highly similar in color and close together in space, participants were most likely to provide a color response biased away from the competitor on the color wheel. A two-way ANOVA investigating the effects of object group (control vs. paired) and object distance (90 px vs. 540 px) showed this effect of group was marginally significant, $F(1, 39) = 2.97, p = 0.09$, such that the paired group ($M = 0.29, SD = 20.58$) tended to show more color repulsion than the control group ($M = -1.81, SD = 18.32$). The paired group had more responses biased away from the competitor than the control group. The main effect of distance, $F(1, 39) = 0.19, p = 0.66$, was not significant, such that the 90 px condition ($M = -1.02, SD = 18.71$) did not significantly differ from the 540 px condition ($M = -0.50, SD = 20.27$). The interaction also failed to reach significance, $F(1, 39) = 1.18, p = 0.28$, indicating that the effect of object similarity on color repulsion did not depend on pair mate distance. We also completed additional analysis to investigate whether or not the 90 px distance color repulsion differed between the two groups. Although this t -test was only marginally significant, $t(39) = -1.77, p = 0.084, 95\% CI = [-6.77, 0.45]$, the data trends were in the predicted direction.

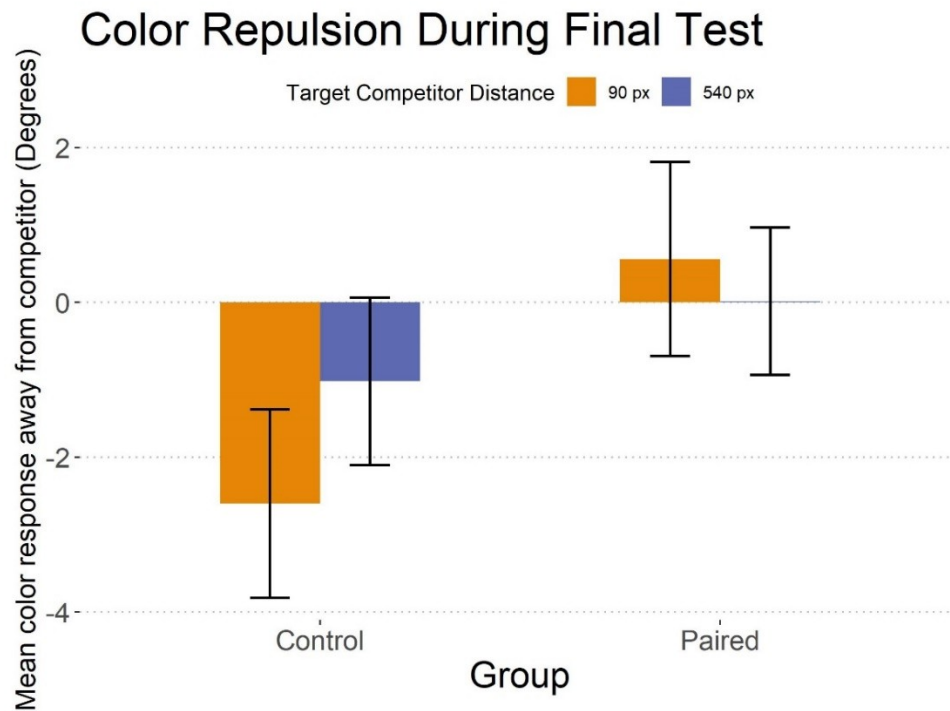


Figure 6. Color repulsion as measured based on color memory response in relation to competitor

Mean color response away from competitor calculated based on location of target on the color wheel, measured in degrees. Zero degrees represents a perfectly correct color response on the color wheel.

Categorical Measure of Color Repulsion: Color Away

We employed a second color repulsion measure that we termed “color away” or the percentage of positive bias (responses biased away from the competitor) by object group and by location. Unlike the previous measure, this is a categorical measurement and is less biased by repulsion errors. Objects that had positive color bias, i.e. were placed farther away from the competitor on the color wheel were given the value of 1 to indicate color repulsion, whilst the responses that were biased toward the competitor received a value of 0. These were averaged across all four final testing rounds, across

all participants and transformed into percent values. We completed a two-way ANOVA, with factors of distance (90px vs. 540px) and group (paired vs. control), and found a marginally significant main effect of object group $F(1, 39) = 3.11, p = 0.09$. As shown in Figure 7, participants demonstrated greater color repulsion away from the competitor in the paired group ($M = 0.49, SD = 0.16$) than in the control group ($M = 0.44, SD = 0.16$). In other words, ignoring spatial location, when memories were highly similar due to identical object identity and high color similarity, we observed a trend towards repulsion and thus, differentiation. The main effect of distance was not significant, $F(1, 39) = 0.09, p = 0.76$. The 90 px distance ($M = 0.46, SD = 0.16$) did not differ from the 540 px distance ($M = 0.47, SD = 0.17$).

Originally, we asked whether color repulsion occurred when a visual spatial aspect was introduced in a task. Moreover, we are interested if color differentiation depended on spatial distance, which is to say we are interested in the interaction of color and location memory. This interaction was not significant, such that the effect of object similarity on color differentiation did not depend on spatial location, $F(1, 39) = 0.37, p = 0.55$. We completed a final analysis to compare the color repulsion in the paired and control group for the 90 px condition. The test was not significant, $t(39) = -1.68, p = 0.10, 95\% CI = [-0.14, 0.013]$, although in the predicted direction.

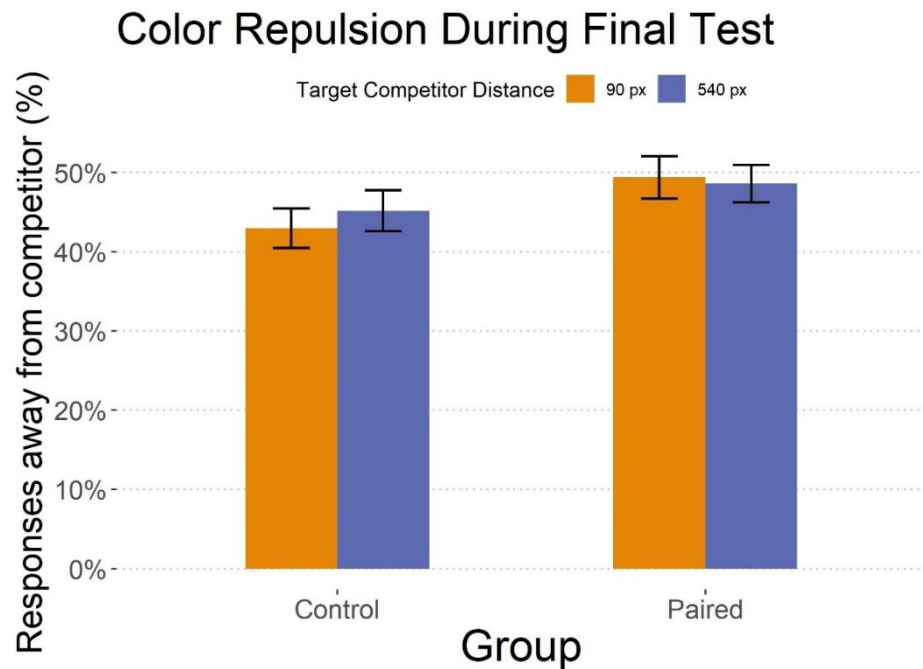


Figure 7. Color repulsion during final testing phase as measured by percent responses away from competitor

Color Selection Ranges

Lastly, in order to investigate the subtler nuances in color repulsion, we measured the percent responses in different color selection ranges that were systematically biased away or towards the competitor. This time, we specified four groups in order to characterize the kind of memory responses participants provided. We generated four different color wheel response ranges as show in Figure 8 below. The first two categories are considered “away” from the competitor. “Correct away” refers to responses 11.25 (or less) degrees away from the target location and away from the competitor, thus still in a range very close to the correct target color. “Error away” refers to any response greater than 11.25 degrees on the color wheel away from both the target and competitor. Likewise, the “towards” group reflects the responses biased

toward the competitor. “Correct towards” includes responses 11.25 (or less) degrees away from the target towards the competitor, which we still consider correct, since they are close to the correct target color. “Error towards” refers to responses greater than 11.25 degrees away from the target towards the competitor, and can thus be considered incorrect.

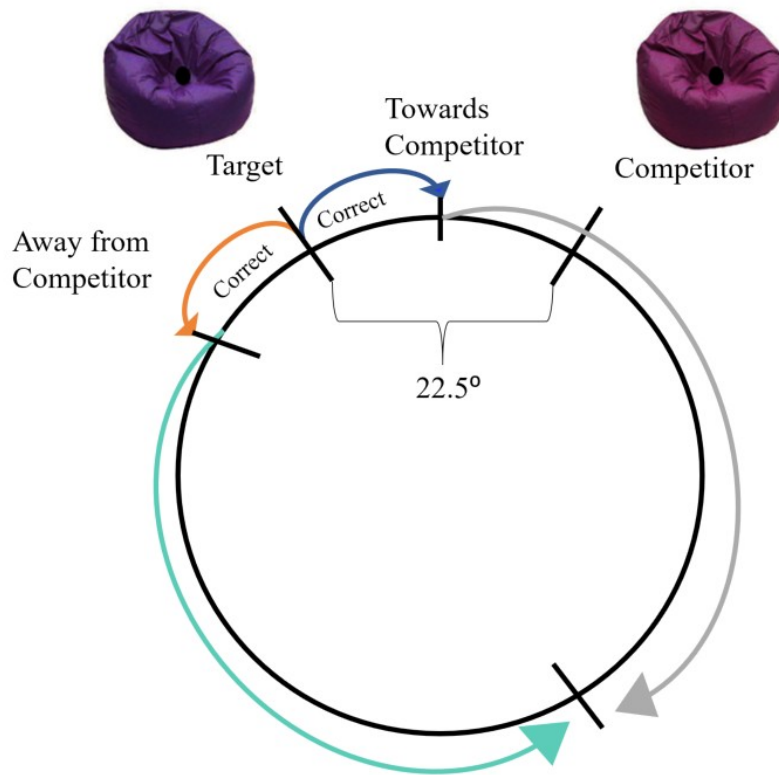


Figure 8. Ranges of color repulsion and attraction

A visual inspection of Figure 9 suggests that the “error away” measure (i.e. repulsion from competitor) was greater than the “error towards” measure (i.e. attraction toward competitor) in the paired group for both distances. The inverse is true for the control group. This indicates far repulsion from the competitor in the paired group, possibly suggesting that when repulsion occurs, we observe a large behavioral gradient

in the difference between the target color and the fully differentiated color. A factorial ANOVA was conducted to investigate the main effects of color choice, group, and distance and it showed a main effect of color choice, $F(2.36, 92.11) = 7.47, p = 0.0005$.

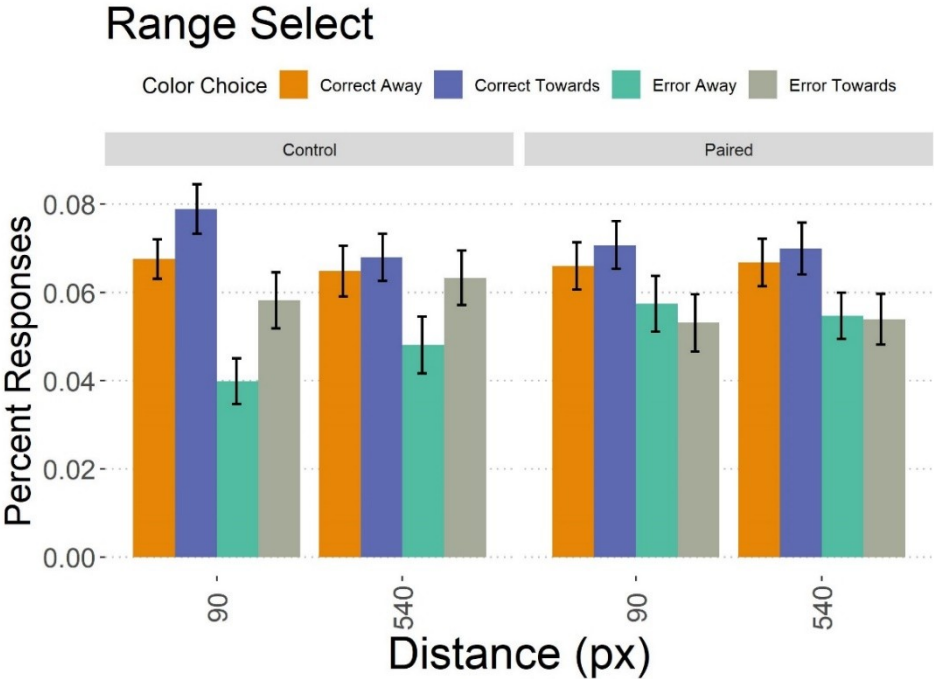


Figure 9. Color repulsion and attraction measured in four different color ranges

“Away” signifies the target object was repelled from competitor, “towards” signifies the target object is attracted towards the competitor. “Correct” ranges refer to responses deemed close enough to the correct target color to be considered accurate.

Color Repulsion as an Adaptive Process

As established by prior research, repulsion often led to a reduction in errors on a given memory task leading researchers to the important conclusion that differentiation was adaptive; in that it aided in eliminating confusion. In our original inquiry, we set out to investigate whether differentiation was related to better performance. To answer this question, we investigated the linear correlation between the mean location error and

positive color bias. Mean location error is the difference in location between subjects' response (measured in pixels) and the correct location in the direction that was *not* of interest (remember, competition was induced in only one direction). Positive color bias in this plot is the same variable as analyzed previously, this time only including data specifically for the paired group. We found a significant linear relationship, $r = -0.313$, $t_{(38)} = -2.033$, $p = 0.0491$, such that greater repulsion from the competitor in the highly similar paired group was associated with smaller location errors (see Figure 10). This goes to say, that although the main effect of location in the analysis of color repulsion was not significant, we see that color differentiation relates to improved memory performance on the associated task.

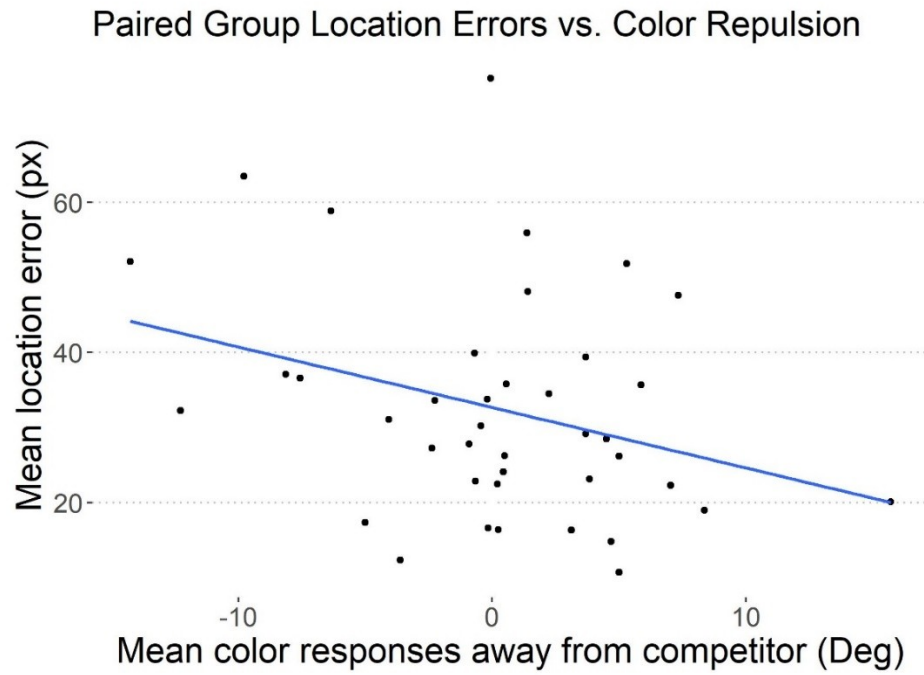


Figure 10. Linear correlation between errors in location memory and color repulsion for the paired object group

Positive values demonstrate color responses away from the competitor, negative responses indicate color responses attracted towards the competitor. Zero degrees represents perfectly correct color response on the color wheel.

Discussion

In the current study, we examined differentiation in the context of a color memory task with an added element of visual space. We set out to investigate whether or not differentiation applied to color memory when a visual spatial element was introduced. We found a marginally significant effect suggesting that indeed, color memory differentiated when memories had a high degree of object similarity. We successfully observed this process in the color memory responses, which is to say we observed it behaviorally. Based on the observations of participants' color memory in a visual spatial context, we found a significant negative linear correlation between location error and color repulsion suggesting that a greater degree of color differentiation is related to decreased errors in spatial location memory. One could make the further conclusion that the process of differentiation helps to prevent memory errors in location, and thus confusion, rendering it adaptive. In this sense, our results are in harmony with previous findings by Chanales, Tremblay-McGaw, and Kuhl (in review), in that we observed color repulsion for objects with a high degree of similarity. We come to a similar conclusion as the aforementioned group of researchers, namely that differentiation aids in memory processing, is competition dependent, and is thus induced by a high degree of similarity.

Difference, not similarity, is necessary in order to create meaning. Paul Cilliers in "Critical Complexity" a series of collected essays illuminates this fact (Cilliers, 2016). For something to be recognizable as this "something," it must be differentiable from others. Under a philosophical lens, Saussure's theory of language as a system of differences demonstrates this concept. According to Saussure, meaning is not

established by an a priori identity, but by a meaningful set of relationships in a system. Take, for example meaning in language. The word “red” does not contain any meaning in itself, because it does not contain the essence of “redness.” Instead, the word “red” is differentiated from other related signifiers like “white,” “pink,” and “brown.” The meanings of these words are determined from interacting relationships of components in a system. Thus, the relationships between these components are measures of differences. Freud’s neurological model of the brain embraced this concept in the context of neural pathways. No one neuron is significant on its own. A series of unique neuron connections, or neural networks, allows memories to be built, stored, and maintained. Thus, memory itself is a system of differences.

Hulbert and Norman (2014) conveyed this sentiment in a neural networks model of memory differentiation, in which the key mechanism, as summarized by Chanales et al. (in review), is the process of repeated retrieval and learning. In simple terms, practice makes perfect, or rather, practice makes different. Repeated retrieval weakens representational overlap among highly similar memories, while repeated interleaved study periods strengthen the unique features of the memory. Similarly to Chanales et al. (in review) and Hulbert and Norman (2014), we employed a study-test experimental paradigm in order to successfully induce differentiation. In Hulbert and Norman’s neural networks model, individual neurons code for individual memory features. These neurons are integrated into a neural network, thanks to their mutual neural connections which can be weaker or stronger based on Hebb’s Rule: neurons that fire together wire together. With repeated retrieval, the neural connections responsible for coding for a memory feature are activated, along with their related connections to the highly similar

memory. A key concept is that these related connections are only weakly activated, and become subsequently weaker with more retrieval practice. When the memory is studied and restudied, the neural connections that are unique to the given memory are reactivated, further strengthening the unique neural connections coding for said memory, whereas the overlapping neural network weakens even more. In this way, the information that becomes significant at the neural level is the series of differences that become more pronounced in a system of relationships. This important theoretical frame allows us to understand what is occurring on a neural level when participants exaggerated the color difference of highly similar memories.

In our statistical analysis, we observed marginally significant effects, but also a fair share of non-significant results. In particular, we were interested if spatial location interacted with color memory for highly similar object pairs. We did not find support for our original prediction, that memory performance for color depended on spatial location. The main effect of location was not significant, neither was the interaction. These results suggest that in human memory, color is exaggerated as an adaptive brain remedy to highly confusable similar memories. The spatial location of the objects could matter less in distinguishing two highly similar memories. Here, we might use the metaphor of a computer to aid our understanding of the observed phenomenon. A computer does not care about the negative space between two objects, but rather cares about their identities. It seems that in this specific context, the dominant memory feature the brain differentiates or manipulates is color. Continuing the metaphor of memory as computer, it could be an energetically conservative choice to differentiate color irrespective of object location. Color exists in one dimension only, as illustrated

by a color wavelength spectrum. Space, on the other hand, has two dimensions in this computer task: an x and a y direction. Although we only manipulated location in either the x or y direction, the human memory system would nevertheless have to hold more data in mind about both the x and y distance of a target and competitor pair in order to successfully manipulate color more or less, depending on how close together the objects were. This would take additional energy allocation and computational space. It is also noteworthy, that color may be intrinsically related to the identity of the object because it informs *what* the object is, unlike its location which only informs of *where* the object is.

Considering that object identity, and not space, was the dominant memory feature used to disambiguate the highly similar memories, one might wonder about the degree of competition we were able to successfully induce in spatial location, even though successful learning occurred. One might also wonder about the role of the hippocampus in performing spatial differentiation. As previously mentioned, imaging studies suggest that the hippocampus, responsible for memory as well as spatial navigation processes, is involved in the general process of differentiation. The implications of these findings give rise to new questions about the specific mechanism involved in the neurological processes behind differentiation, if in fact human memory is selective of certain memory features over others, and how potential overlapping memory features fit into neural networks.

It is prudent to consider possible limitations in the experimental design of this study. The most salient limitation, is the fact that this task is very challenging in and of itself. Attending to each object during its presentation, completing a slew of learning memory tests about location and color, followed by final testing rounds was taxing on

many of the participants. The task took an hour to complete, by the end of the hour, participants were likely to be mentally fatigued, meaning other processes important for memory formation such as attention and encoding could have easily been overloaded. Future studies may include simpler study designs with fewer to-be-remembered items. Another issue encountered in data analysis were the swap errors participants made. It was not difficult to accidentally swap the target and competitor object due to their high degree of similarity. This would result in extreme memory responses on both the color test and location test, suggesting extreme repulsion or attraction. Our continuous measures of color memory are especially susceptible to this common error. In future investigations, it would be prudent to devise a method by which we could parse out swap errors to omit those data from the final data analysis, considering it could potentially drive the results in one direction over another.

The main take home lesson from the story of these data is that the human brain has adapted to resolve memory conflicts which arise due to a high degree of similarity. Similarity induced color repulsion, just like two positive poles of a magnet brought together that subsequently repel from their counterpart. The body of existing literature, as well as the effect of color repulsion found in our study, although marginally significant, suggest that differentiation is an important mechanism that enables us to create mental contrast and simplify complexity, thus making sense of the world around us.

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