Quantity vs. Quality:

Individual Differences in Capacity and Resolution of Visual Working Memory

by

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Abstract

We took an individual differences approach to investigate the relationship between capacity and resolution in visual working memory. Capacity was measured using a visual change detection task. Color resolution was assessed using a color wheel task (Wilken & Ma, 2004), while spatial resolution was assessed using a novel spatial analog of the color wheel task. We demonstrated that working memory resolution is a reliable individual difference. Performance on the color and spatial resolution tasks were positively correlated, and efforts to distinguish the two domains via behavioral traits and skills were non-significant. Notably, we found that higher capacity is related to higher resolution in both color and spatial domains. This implies that capacity and resolution are not independent constructs. Our findings support the flexible-resource models of working memory.

Quantity vs. Quality:

Individual differences in Capacity and Resolution of Visual Working Memory

One of the hallmark characteristics of visual short-term memory is its limited capacity (Alvarez & Cavanaugh, 2004; Luck & Vogel, 1997). Individuals can remember approximately four items, but researchers have reported individual differences in capacity ranging from two to six objects (Todd & Marois, 2004). Despite the great deal of research regarding the number of items that can be represented in working memory, there has been little research until recently regarding the resolution, or precision, of representations.

The main focus of this recent work has been to compare two possible models of visual working memory: 1) a fixed-slot model, in which an individual can hold in memory a small set of items with fixed resolution, and 2) a flexible-resource model, in which individuals can flexibly allocate resources such that they can hold fewer items of high resolution or more items with lower resolution depending on task demands (Awh, Barton, & Vogel, 2007; Barton, Estes, & Awh, 2009; Bays & Husain, 2008; Bays, Catalao, & Husain, 2009; Wilkin & Ma, 2004; Zhang and Luck, 2008; Zhang and Luck, 2009). The studies in this body of work primarily vary the complexity of the stimuli, the number of objects to be encoded, or other task characteristics and assess how they affect performance. Another way of assessing independence between capacity and resolution is to use an individual differences approach (Fukuda, Awh, & Vogel, 2010). A flexible-resource model would predict a correlation between capacity and resolution because individuals should be able to flexibly allocate their resources to either a large number of coarsely represented objects or a small number of higher resolution objects. A lack of correlation is more consistent with a fixed-slot model (Fukuda et al., 2010).

Awh, Barton, and Vogel (2007) were the first to take an individual differences approach to investigate the relationship between capacity and representation resolution. They employed a visual change detection task where participants had to detect either a cross-category (low resolution) or a within-category (high resolution) change. Performance was lower in the within- than cross-category condition, but critically there was no correlation between capacity on the low resolution trials and capacity on trials requiring high resolution. In a related study in which participants also performed tasks with low and high resolution demands, an exploratory factor analysis supported a two-factor model (Fukuda, Vogel, Mayr, & Awh, 2010). Further, only the low resolution capacity tasks correlated with fluid intelligence. Although these two studies provide some evidence against a flexible-resource model, the results may have been affected by the fact that an indirect measure of resolution was used in these studies. This renders the possibility that performance on "high resolution" trials were influenced by factors besides representation resolution (e.g., probe interference, Makovski, Sussman, & Jiang, 2008).

To address the question of individual differences in resolution and capacity more directly, we used two versions of a cued recall paradigm that yielded continuous measures of resolution for color and spatial location (Wilken & Ma, 2004; Zhang & Luck, 2008). In the color resolution task, participants viewed a number of colored objects. Following a delay, one object was cued spatially and the participants' task was to recall the color of the cued object using a color wheel that appeared on the screen (see Figure 1). The angular distance of participants' response to the actual target was used in measuring color resolution. In the spatial analog of the color resolution task developed for this study, participants were presented with a set of colored objects identical to those used in the color wheel task. After the delay, one object appeared in the center of the screen and the task of the participant was to use the mouse to re-position the object to its original location (see Figure 2). The Euclidean distance between the participants' selected location and the target location was used as a measure of spatial representation precision. For both the color and spatial resolution tasks, we fixed the number of objects on the screen to three, which was suggested to be approximately at or below most individuals' capacity (Cowan, 2001).

By using two distinct tasks for resolution, we test the construct of resolution being comprised of multiple domains. Prior studies asserting a fixed-slot model have employed a unitary construct of resolution (e.g., Zhang & Luck, 2008). The presence of multiple domains for resolution would beg for further study into their individual correlations with capacity, as well as with each other. To assess capacity, a standard visual change detection paradigm was used, and the array size was varied from two to ten (see Figure 3). Note that the visual change detection task has relatively low-resolution demands (Awh et al., 2007) and is commonly used as a measure of individual differences in capacity (Cowan, 2001).

Investigating the relationship between capacity and resolution requires that individuals systematically vary in terms of both constructs. Moreover, we wanted to examine if these individual variations in capacity and resolution could be explained by differences in relevant cognitive skills. Several of these have been identified as being correlated with performance on memory tasks, including vivid visualizations (Marks, 1973) and object-spatial imagery skills (Blajenkova, Kozhevnikov, & Motes, 2006). We asked if the relationship between these cognitive skills and visual working memory was preserved in our continuous and distinct measures for capacity and resolution. In addition, a high representation resolution requires precision, and prior research has suggested a correspondence between precision and perfectionist tendencies (Allsopp & Verduyn, 1990). Participants completed three questionnaires assessing their vividness of visual imagery, object-spatial imagery skills and level of perfectionism. Questionnaire results were then compared against scores on capacity and resolution tasks.

An outline of the study is as follows: we first assessed the reliability of each resolution task. That is, we asked whether or not there are individuals who systematically maintain high-resolution representations and others who systematically maintain low-resolution representations in working memory. Next, we examined whether or not resolution for color information and resolution for spatial location information were related. Third, we assessed the relationship between the two resolution measures and capacity. Finally, we considered relevant behavioral traits and skills that might predict individual variations in capacity and resolution.

Method

Participants

There were 103 students aged between 18 and 23 from the University of Michigan, Ann Arbor who participated in this study. Of these, 43 participants were paid $15 to complete the study, while 60 participants were granted course credit. All participants reported normal color vision as well as normal or corrected-to-normal visual acuity.

Materials and Apparatus

Color resolution task. (See Figure 1.) We used a variant of the color wheel task reported in Zhang and Luck (2008) to measure the color resolution. On each trial, we presented viewers with three colored squares (2° each side) for 500 ms, in one of eight predetermined locations on an invisible circle with a radius of 7.5°. The colors were randomly chosen from a set of 180 colors making up the color wheel, with the constraint that each color pair was at least 20 degrees apart on the color wheel. Then, following a 900 ms delay, the response display appeared, and remained on until a response was made. In the response display, there was both the color wheel and placeholders for the 3 objects that had been presented. The color wheel and the squares were presented on the same gray background. The color wheel had a radius of 11° and was 3.5° thick and consisted of 180 differentiable colors with each color covering 2° of the wheel. The placeholders were frames outlining the positions of the previously shown colored squares, but one of them was made thicker to identify the target square. The participants were asked to recall the color of the target square and choose it from the color wheel by a mouse click. The coordinates for these mouse clicks were recorded.

For each trial, the error margin was computed as such: first, the angular deviation between the target and the chosen color on the color wheel was calculatd. RGB values corresponding to the cue and the target were identified, and their intermediary distance was calculated in a three-dimensional RGB color space using the Euclidean formula. The maximum difference possible between any two chosen colors was 353 units.

Participants completed four calibration trials, followed by five practice trials and 115 experimental trials. The calibration trials were included to control for possible color perception error and clicking precision. In such a trial, a colored square was presented inside of the color wheel until participants had visually matched the color of the square by clicking on its corresponding shade on the color wheel. The experimental trials were analyzed after subtracting the mean error from the calibration trials. After each response in the experimental trials, participants were asked whether they had guessed on the trial. They pressed “Y” on the keyboard to indicate that they had guessed, or “N” to indicate that they had not guessed.

Spatial resolution task. (See Figure 2.) This was a novel spatial analog of the color resolution task. On each trial, we presented viewers with three colored squares (2° each side) for 500 ms, in one of eight predetermined locations on an invisible circle with a radius of 7.5°. This time, the colors of the squares were consistent across all trials. On each trial, there would be one red square, one green square, and one blue square. Following a 900 ms delay, the response display appeared, and remained on until a response was made. In the response display, the cue is positioned in the center of the screen as a colored square. Participants were asked to recall the spatial location of that square by re-positioning the square on the screen and clicking the mouse. The coordinates for these mouse clicks were recorded. The error margin was calculated as the Euclidean distance between the target location and the location clicked on the screen.

Participants completed five practice trials and 115 experimental trials. Only the experimental trials were analyzed. After each response in the experimental trials, participants were asked whether they had guessed on the trial. They pressed “Y” on the keyboard to indicate that they had guessed, or “N” to indicate that they had not guessed.

Vividness of visualizations. The Vividness of Visual Imagery Questionnaire (VVIQ; Marks, 1973) was employed to test for possible correlations of visualization skills with capacity and resolution. Participants were asked to visualize specific scenes (e.g., “The sun is rising above the horizon into a hazy sky”), before rating the vividness of their mental imagery on a 5-point scale, from “*Perfectly clear and as vivid as normal vision*” to “*No image at all, you only 'know' that you are thinking of an object*”. The questionnaire is listed in Appendix A.

Perfectionism. The Multidimensional Perfectionism Scale (Frost, Marten, Lahart, & Rosenblate, 1990) was predicted to account for the precision-driven nature of working memory resolution. Perfectionism was categorized into six dimensions: 1) Concern over Mistakes (e.g., “People will probably think less of me if I make a mistake”), 2) Personal Standards (e.g., “If I do not set the highest standards for myself, I am likely to end up a second-rate person”), 3) Parental Expectations (e.g., “My parents have always had higher expectations for my future than I have”),

4) Parental Criticism (e.g., “As a child, I was punished for doing things less than perfect”), 5) Doubts about Actions (e.g., “I tend to get behind in my work because I repeat things over and over”) and lastly, 6) Organization (e.g., “Neatness is very important to me”). Participants stated whether they agreed or disagreed to statements about themselves on a 5-point scale. The questionnaire is listed in Appendix B.

Object-spatial imagery skills. The Object-Spatial Imagery Questionnaire (OSIQ; Blajenkova et al., 2006) examines styles of information representation and how that relates to working memory. The Object subscale measures the tendency for one to represent information as colorful and vivid images (e.g., “My images are very colorful and bright”), while the Spatial subscale measures the preference for using schematic diagrams and spatial relations (e.g., “I can easily imagine and mentally rotate 3-dimensional geometric figures”). Participants stated whether they agreed or disagreed to statements about themselves on a 5-point scale. The initial hypothesis was that the Object subscale would correlate with color resolution while the Spatial subscale would correlate with spatial resolution. The questionnaire is listed in Appendix C.

Visual change detection task. (See Figure 3.) On each trial, a fixation cross was presented for 1000 ms and was followed by a presentation of the first array of squares for 250 ms. The array size varied randomly between 2, 4, 6, 8 and 10 squares. The square colors were red, blue, violet, green, yellow, black, and white, and each square was assigned a color randomly with replacement. Correct responses based on guessing is minimized with no restriction against the same color appearing more than once in an array. There was a 1000 ms delay interval preceding a second array. In the second array, one of the squares will be circled. This indicated that the color of that particular square might have changed from the first array, and the participants were asked whether or not they thought this was the case. They pressed “A” on the keyboard to indicate that the square's color had changed, or "L" to indicate that the square's color was the same as before. This experimental procedure was considered the most appropriate for judging storage capacity because only one decision had to be made (on the cued square), limiting interference (Luck & Vogel, 1997). Participants were given feedback after each trial. This task consisted of 10 practice trials followed by 150 experimental trials. There were 30 experimental trials at each array size.

The capacity estimate was computed as follows: let N be the array size and let k be the number of items transferred into working memory. Then k/N would represent the probability that a participant would answer correctly based on what was encoded into his memory. This leads to the formula $k = N * (H - FA)$, as established by Cowan (2001), where H is the proportion of hits and FA is the proportion of false alarms (proportion of "change" responses, when in fact no change occurred). k is expected to increase with the array set size until it reaches a plateau, at which k = capacity.

Procedure

After informed consent, participants performed the color resolution task followed by the spatial resolution task. Both of these were done on the computer. Then, they filled out pen-and-paper questionnaires. The questionnaires were in the order: 1) vividness of visualizations, 2) perfectionism level, and 3) object-spatial imagery skills. Next, participants performed the visual change detection task on the computer. They concluded the study by completing a pen-and-paper demographics questionnaire. All computerized tasks were presented at a viewing distance of 57 cm on LCD monitors with resolution 640x480 pixels.

Results

In the formal analysis pertaining to our hypotheses, we used only “remember” trials and excluded all “guessed” trials from the resolution tasks. The goal was to filter out the trials on which participants guessed so that we only measured resolution for when the cue was successfully encoded into working memory. In the color resolution task, participants on average guessed on 15.91% of trials. A paired t-test revealed that mean error on “guessed” trials (M=167.14) was significantly higher than mean errors on “remember” trials (M=146.68), $t(101)=5.55$, $p<0.001$. In the spatial resolution task, participants on average guessed on 3.75% of trials. There are two possible reasons for a lower rate of guessing on the spatial task. Participants could have found the spatial resolution task to be easier, or they were not cognitizant of how they were responding, or both. However, a comparison revealed that the mean error on “guessed” trials (M=27.06) was once again significantly larger than the mean error on “remember” trials (M=5.32), $t(101)=6.00$, $p<0.001$. To account for differences in variability in the “guessed” and “remember” trials, we conducted an additional nonparametric test to assess the difference in mean errors, which was also significant, $Z=4.73$, $p<0.001$.This indicates that participants had some subjective awareness of their performance, and supports the exclusion of “guessed” trials for accurate analyses.

The first question we asked was whether there were individual differences in visual working memory resolution. In order to determine how consistent participants were across all the trials, we calculated Cronbach’s alpha as a reliability index. Cronbach’s alpha was computed using the error for all “remember” trials of the full sample. In the color and spatial resolution tasks, Cronbach’s alpha was 0.92 and 0.93 respectively, suggesting that people were highly consistent in how well they represented and recalled color and spatial information. There was observable between-subject variation while within-subject variation across trials was minimal (see Figures 4a and b). Specifically, the mean standard errors for individuals were highly similar in both the color resolution task (M=10.84, SD=0.60) and spatial resolution task (M=14.83, SD=1.91). Hence, our results support our first hypothesis; there are stable individual differences in representative resolution.

Next, we examined if color resolution was related to spatial resolution. To determine whether individuals with high resolution for color information also had high resolution for spatial information, we computed correlations between the mean errors in the color and spatial resolution measures. As seen in Figure 5, color resolution was significantly and positively correlated with spatial resolution, $r(103)=0.24$, $p=0.022$. This implies a common resolution construct that underlies our subtasks in the two domains of color and space.

The third goal was to study the relationship between the two resolution measures and capacity. A capacity estimate was computed for each participant based on their performance on the visual change detection task. The formula is stated in the Method section. As depicted in Figures 6a and b, mean resolution errors decreased as capacity increased ($r(103)=-0.21$, $p=0.045$ and $r(103)=-0.31$, $p=0.003$ for color and space respectively). This is strong evidence suggesting that individuals with higher working memory capacity are also able to represent information more precisely.

Finally, we examined whether behavioral traits and skills might predict individual variations in capacity and resolution. Table 1 lists the correlation matrix. A significant albeit mystifying correlation was found between spatial resolution and perfectionism, $r(103)=0.22$, $p=0.036$. Since spatial resolution was defined in terms of error, a positive correlation implied that people who reported overall higher levels of perfectionism committed more errors on the spatial resolution task. This phenomenon was totally absent for the color resolution task, whereas positive correlations with spatial resolution error held for three out of the six dimensions of perfectionism. Notably, the Organization dimension exhibited a negative correlation with spatial resolution error that was approaching significance, $r(103)=-0.20$, $p=0.069$. Different patterns of association with perfectionism might be attributed to technical differences in task setups. The other correlations between questionnaire scores and capacity/resolution were non-significant.

Discussion

This study demonstrated that individual differences in representation resolutions are reliable measures. Color and spatial resolution are both correlated with visual working memory capacity, and are significantly correlated with each other. This suggests a common resolution construct that underlies both domains. These findings have implications for the ongoing debate on the nature of visual working memory representations.

Even though there are a small number of recent studies that have attempted to measure representation resolution, there is no clear consensus on how representation resolution should be assessed. In this paper, we presented two recall tasks that provided continuous measures of resolution in both color and spatial domains, the latter being a novel working memory task analogous to the color wheel task employed in recent work (e.g., Bays et al., 2010; Wilken & Ma, 2004; Zhang & Luck, 2008). This study is the first to demonstrate that representation resolution is a reliable construct. Despite the fact that representation resolution varies amongst people, individuals are rather consistent in how precisely they can represent information in working memory.

The most theoretically interesting finding is the relationship between capacity and resolution in both color and spatial domains, consistent with the flexible-resource accounts of working memory capacity (Bays & Husain, 2008). According to such models, individuals have finite working memory resources that are distributed in smaller amounts as the number of to-be-remembered items increases. Thus, these models would predict that when there are only a few to-be-remembered items, individuals with greater resources would be able to allocate more to each individual item resulting in higher precision. A related but somewhat distinct explanation is that individuals with more mental resources are better able to strategically allocate those resources depending on task demands. The visual change detection task used in this study required relatively coarse coding of information, whereas the color wheel and spatial cued recall task emphasized high-resolution representations.

The relationship between capacity and resolution is consistent with related work on video game players. Action video game players are known to have higher working memory capacity (e.g., Green & Bavelier, 2003); and were recently shown to be able to form more precise color representations in a color wheel task (Sungur & Boduroglu, under review). Similarly, it has been demonstrated that higher capacity was associated with higher precision in a spatial working memory task (Walsh, Gmiedl, Marchette, Shelton, & Fornbaum, under review). There is a growing body of evidence suggesting that working memory capacity may not be independent of representation resolution contrary to earlier accounts (e.g., Xu & Chun, 2006; Zhang & Luck, 2008). The findings in this study are also in contrast to findings reported by Awh et al. (2007). In their study, they measured resolution by performance on visual change detection tasks that they assumed differed primarily on resolution demands. Specifically, they found that performances on high- and low-resolution conditions were not correlated despite the fact that the high-resolution versions were highly correlated. However, it is possible that performance in especially the high-resolution conditions was influenced by factors besides resolution. For example, the high-resolution conditions might have involved greater probe interference or that some participants disengaged from both of the high resolution demanding tasks. These same individuals may not have disengaged from the low-resolution tasks. Thus, these factors might have inadvertently affected the lack of correlation between high- and low-resolution conditions.

Interference processes may be the underlying explanation for the relationship between capacity and resolution. If individuals have coarse representations, there will be greater interference between to-be-maintained items. By contrast, individuals with more precise representations should be able to maintain more distinct items in their working memory (Walsh et al., under review). Thus, individual differences in working memory resources may actually arise because of distinctiveness or precision of representations (Oberauer, 2002). Such an explanation would account for the association between color and spatial resolution as well as the significant correlation with capacity for both resolution modalities.

The final piece of finding demonstrated a curious relationship between perfectionism and spatial resolution. Allsopp and Verduyn (1990) observed that perfectionism and precision were frequently exhibited together in patients with obsessive-compulsive disorder. This leads to the intuition that the desire for perfection might translate into better performance on the precision-driven resolution tasks. However, the results of this study ran contrary to this expectation. Not only was color resolution unrelated to perfectionism, three out of six dimensions of perfectionism were positively correlated with error on the spatial resolution task. The three dimensions were Concern over Mistakes, Parental Criticism and Doubts about Actions. A unifying theme for these dimensions might be fear. The fear of failing or being reprimanded might lead to more hesitation when completing precision tasks (Wolff & Wolff, 1991), resulting in a time lag during which memory representations decay. On the other hand, the remaining three dimensions of Personal Standards, Parental Expectations and Organization were more emotionally neutral. The almost-significant correlation between Organization and spatial resolution suggests that this dimension was most relevant to predicting precision objectively.

Technical differences in the setup of the resolution tasks might account for the absence of association between perfectionism and color resolution. Participants only had 180 options on the color wheel to choose from in the color resolution task, compared to 640x480 spatial locations (pixels) in the spatial resolution task. As a result, the spatial resolution task might have yielded a more precise measure of resolution in itself, amplifying the effects of perfectionism. Being a more sensitive measure might also have contributed to the stronger correlation between spatial resolution and capacity, as compared to that between color resolution and capacity.

In addition to clarifying the relationship between perfectionism and resolution, our results prompt additional research into the dissociative nature of resolution. Prior work had argued that color and spatial working memory systems are separable (e.g., Farah, Hammond, Levine, & Calvanio, 1988). Yet, our results demonstrate a positive association between color and spatial resolution, with no conclusive evidence that performance on the two domains might be distinguished on the basis of behavioral traits and skills. Future studies might focus on addressing the distinction between hypothesized domains of representative resolution to reconcile current findings.

References

Allsopp, M., & Verduyn, C. (1990). Adolescents with obsessive-compulsive disorder: A case note review of consecutive patients referred to a provincial regional adolescent psychiatry unit. *Journal of Adolescence, 13,* 157-169.

Alvarez, G.A., & Cavanagh, P. (2004). The capacity of visual short-term memory is set both by visual information load and by number of objects. *Psychological Science, 15*(2)*,* 106-111.

Awh, E., Barton, B., & Vogel, E. K. (2007). Visual working memory represents a fixed number of items, regardless of complexity. *Psychological Science*, *18*, 622-628.

Barton, B., Ester, E.F., & Awh, E. (2009). Discrete resource allocation in visual working memory. *Journal of Experimental Psychology, 35,* 1359-1367.

Bays, P.M., Catalao, R.F.G., & Husain, M. (2009). The precision of visual working memory is set by allocation of a shared resource. *Journal of Vision, 9,* 1-11.

Bays, P.M., & Husain, M. (2008). Dynamic shifts of limited working memory resources in human vision. *Science, 321,* 851-854.

Blajenkova, O., Kozhevnikov, M., & Motes, M. A. (2006). Object-spatial imagery: A new self-report imagery questionnaire. *Applied Cognitive Psychology*, *20*, 239–263.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24,* 87-185.

Farah, M. J., Hammond, K. M., Levine, D. N., & Calvanio, R. (1988). Visual and spatial mental imagery: Dissociable systems of representation. *Cognitive Psychology, 20,* 439-462.

Fukuda K., Awh E., Vogel E. K. (2010). Discrete capacity limits in visual working memory. *Current Opinion in Neurobiology*, *20*, 177-182.

Fukuda, K., Vogel, E., Mayr, U., & Awh, E. (2010). Quantity not quality: The relationship between fluid intelligence and working memory capacity. *Psychonomic Bulletin & Review*, *17*, 673-679.

Frost, R. O., Marten, P. A., Lahart, C., & Rosenblate, R. (1990). The dimensions of perfectionism. *Cognitive Therapy and Research*, *14*, 449-468.

Green, C.S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature*, *423*, 534 -537.

Makovski, T., Sussman, R. S., & Jiang, Y. V. (2008). Orienting attention in visual working memory reduces interference from memory probes. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *34*, 369-380.

Marks, D. F. (1973). Visual imagery differences in the recall of pictures. *British Journal of Psychology*, *64*, 17–24.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*, 279-281.

Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *28*, 411-421.

Sungur, H., & Boduroglu, A. (under review). Action video game playing benefits object resolution.

Todd, J.J., & Marois, R. (2004). Capacity limit of visual short-term memory in human posterior parietal cortex. *Nature*, *428*, 751-754.

Walsh, M. K., Gmeindl, L., Marchettee, S. A., Shelton, A. L., & Flombaum, J. I. (under review). Individual differences in the resolution and capacity of spatial working memory.

Wilken, P., & Ma, W. J. (2004). A detection theory account of change detection. *Journal of Vision*, *4*, 1120-1135.

Wolff, R. P., & Wolff, L. S. (1991). Assessment and treatment of obsessive-compulsive disorder in children. *Behavior Modification*, *15*, 372–393.

Xu, Y., & Chun, M. M. (2006). Dissociable neural mechanisms supporting visual short-term memory for objects. *Nature*, *440*, 91-95.

Zhang, W., & Luck, S.J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature, 453,* 233-236.

Zhang, W., & Luck, S.J. (2009). Sudden death and gradual decay in visual working memory. *Psychological Science, 20,* 423-428.

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Table 1

Correlations between capacity, resolution domains, and questionnaire scores

	1	2	3	4	5	6	7	8	9	10	11	12
1 Capacity												
2 Color resolution (mean error)	-.211*											
3 Spatial resolution (mean error)	-.306**	.236*										
4 Vividness of imagery	-.156	.065	-.009									
5 Object imagery skill	-.091	-.134	-.023	.499**								
6 Spatial imagery skill	.096	.073	.003	.070	.144							
7 Perfectionism - Concern over mistakes	-.082	-.081	.227*	-.070	.036	.088						
8 Perfectionism - Personal standards	.455	.459	.033	.516	.742	.416	.535**					
9 Perfectionism - Parental expectations	.103	-.031	.047	.110	.168	.128	.243*	.196				
10 Perfectionism - Parental criticism	.038	-.078	.225*	.058	.054	.027	.360**	.219*	.552**			
11 Perfectionism - Doubts about actions	-.143	.039	.248*	-.014	.131	.042	.473**	.343**	.233*	.302**		
12 Perfectionism - Organization	.048	-.091	-.195	.019	.094	.205	.166	.188	.033	-.115	.025	
13 Perfectionism - Total	-.068	-.073	.224*	.024	.158	.166	.820**	.709**	.535**	.553**	.597**	.417**

N = 103

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

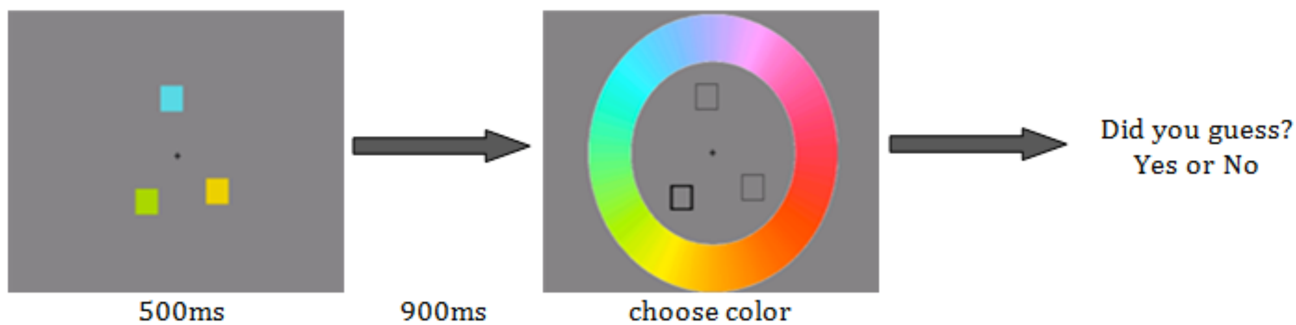

Figure 1. Color resolution task.

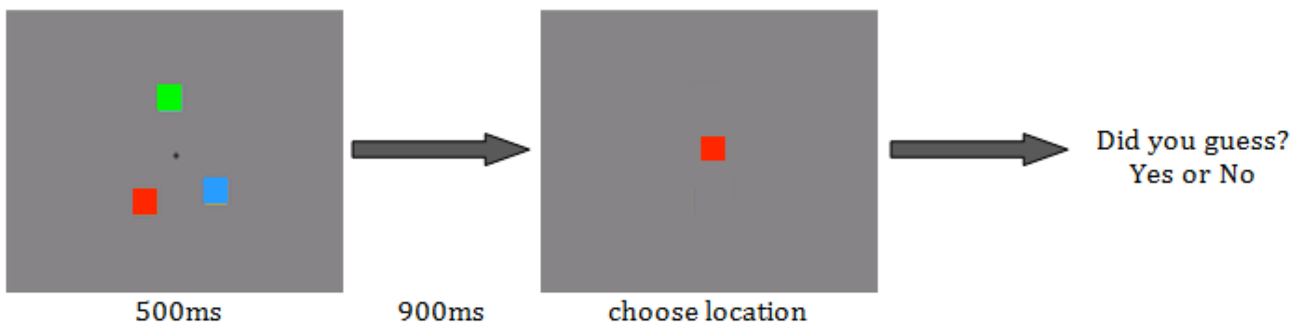

Figure 2. Spatial resolution task.

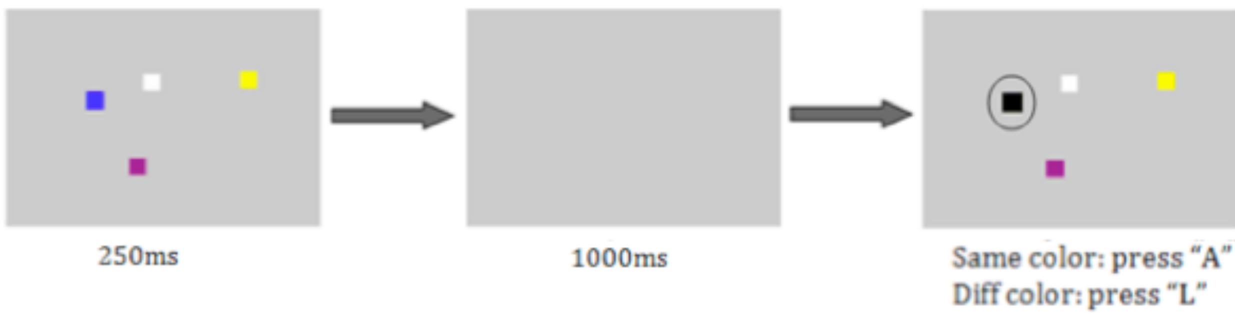

Figure 3. Visual change detection task.

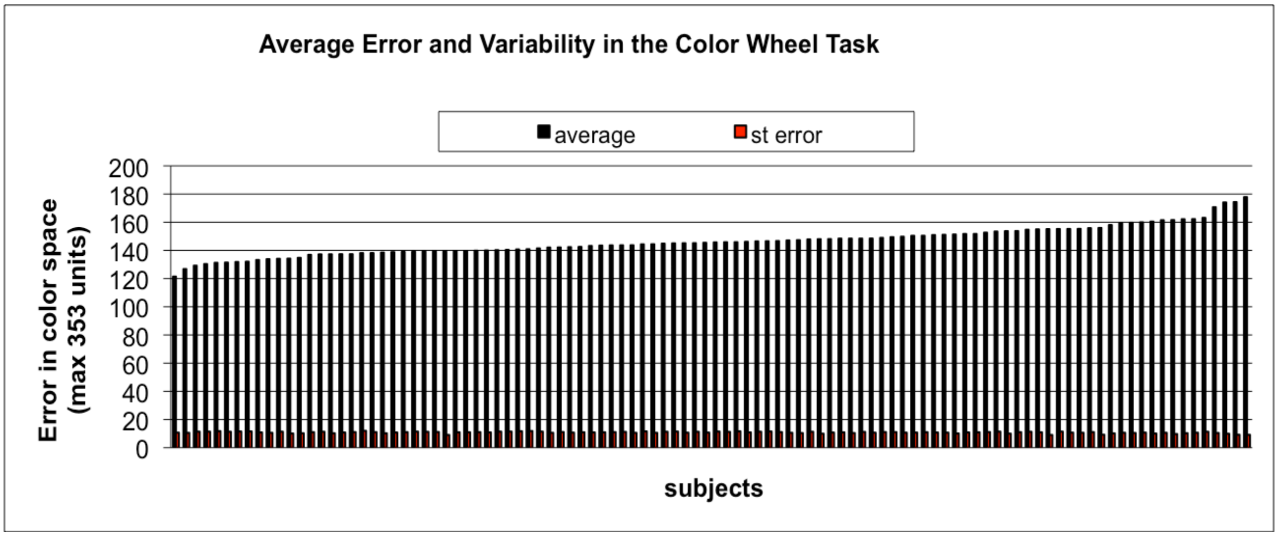

Figure 4a. Individual differences in color resolution.

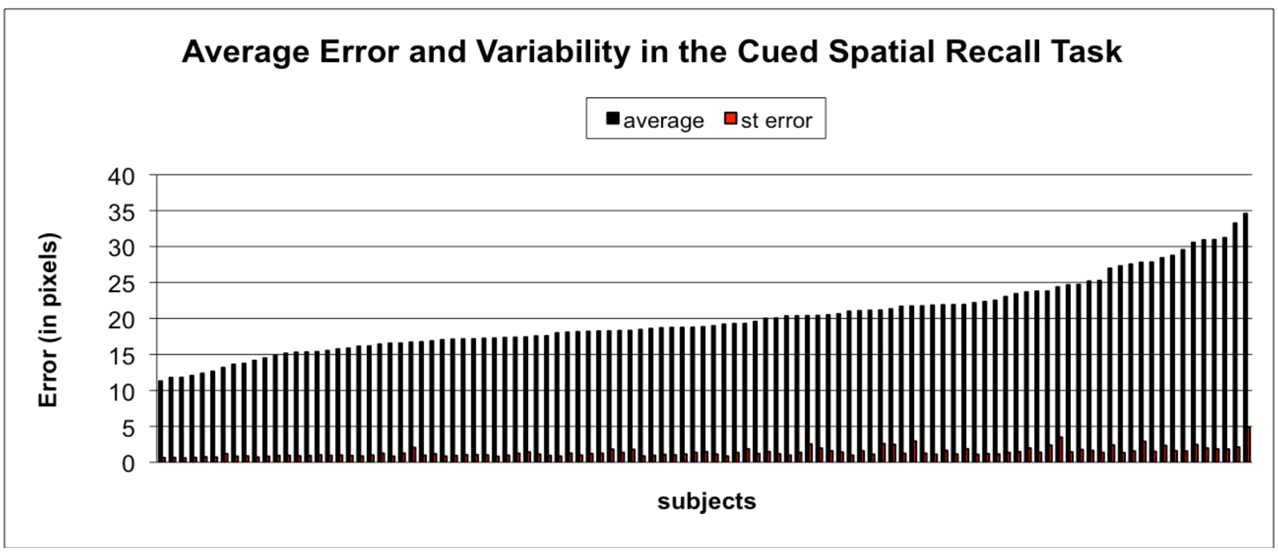

Figure 4. Individual differences in spatial resolution.

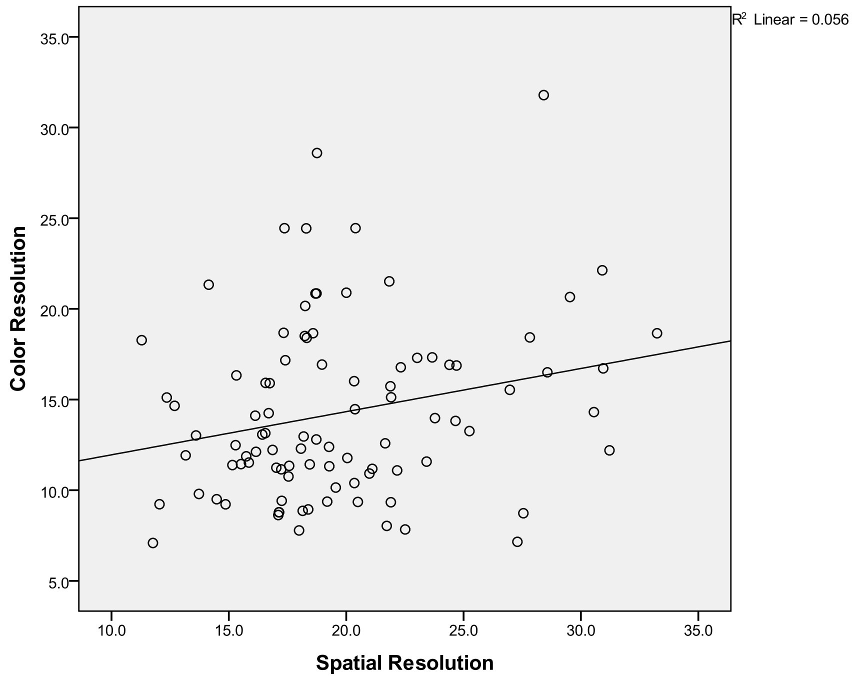

Figure 5. Scatterplot of spatial resolution against color resolution in terms of mean errors.

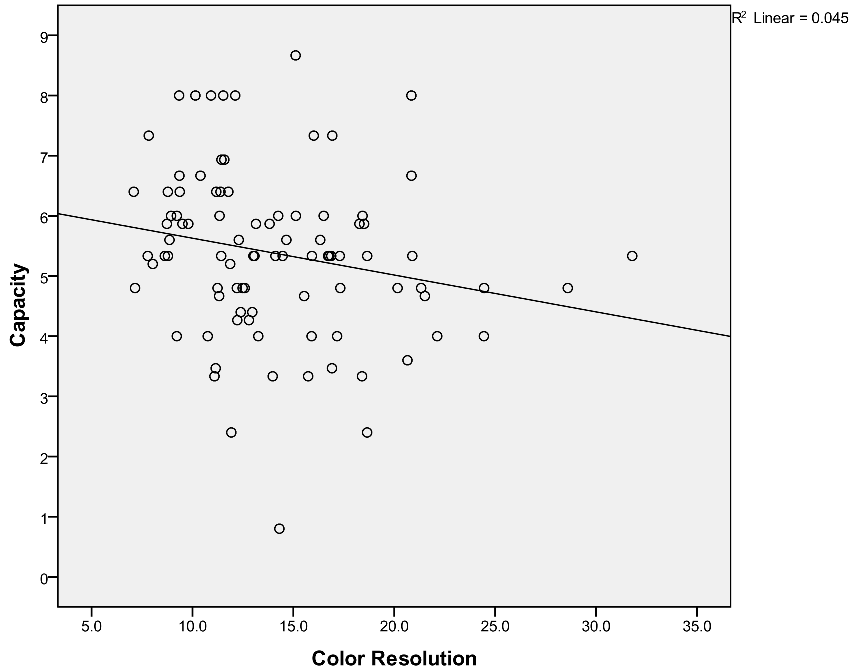

Figure 6a. Scatterplot of the mean errors in color resolution against capacity.

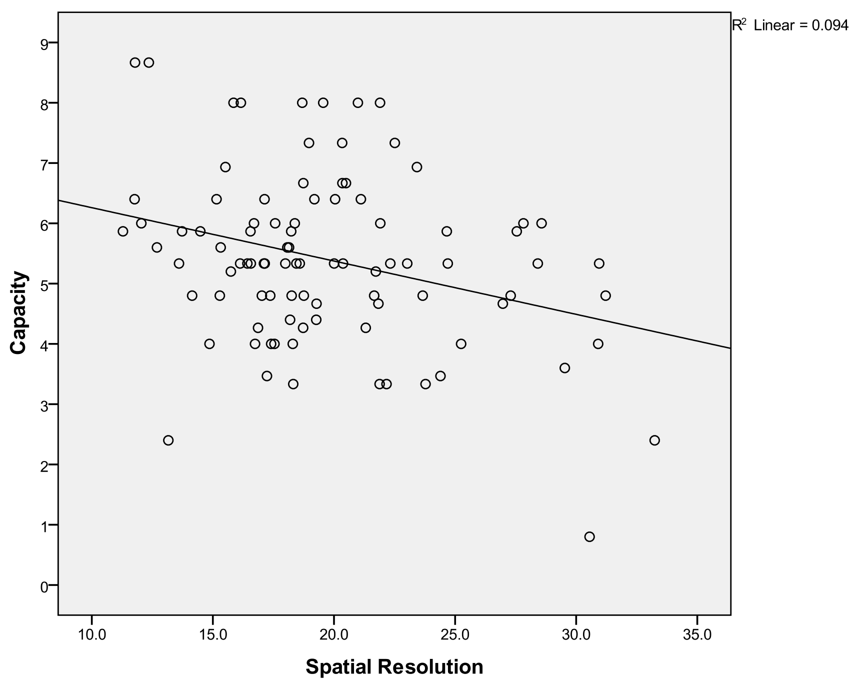

Figure 6b. Scatterplot of the mean errors in spatial resolution against capacity.

Appendix A

Vividness of Visual Imagery Questionnaire

Visualize the following scenarios with your **EYES OPEN**. Please **rate the vividness of each image** using the 5-point scale given below. After completing this questionnaire, you would do it again, this time with your **EYES CLOSED**.

For items 1 through 4, think of some **relative or friend whom you frequently see** and consider carefully the picture that comes before your mind's eye. Circle the number corresponding to the vividness of:

1. **The exact contour of his/her face, head, shoulders and body.**

5 "Perfectly clear and as vivid as normal vision

4 "Clear and reasonably vivid"

3 "Moderately clear and vivid"

2 "Vague and dim"

1 "No image at all, you only 'know' that you are thinking of an object"

2. **Characteristic poses of his/her head and body language.**

5 "Perfectly clear and as vivid as normal vision

4 "Clear and reasonably vivid"

3 "Moderately clear and vivid"

2 "Vague and dim"

1 "No image at all, you only 'know' that you are thinking of an object"

3. The precise carriage and length of stride in his/her walking.

5 "Perfectly clear and as vivid as normal vision

4 “Clear and reasonably vivid"

3 "Moderately clear and vivid"

2 "Vague and dim"

1 "No image at all, you only 'know' that you are thinking of an object"

4. The different colors worn in some familiar clothes.

5 "Perfectly clear and as vivid as normal vision

4 “Clear and reasonably vivid"

3 "Moderately clear and vivid"

2 "Vague and dim"

1 "No image at all, you only 'know' that you are thinking of an object"

For items 5-8, visualize the **rising sun**. Circle the number corresponding to the vividness of:

5. The sun is rising above the horizon into a hazy sky.

5 "Perfectly clear and as vivid as normal vision

4 “Clear and reasonably vivid"

3 "Moderately clear and vivid"

2 "Vague and dim"

1 "No image at all, you only 'know' that you are thinking of an object"

6. The sky clears and surrounds the sun with blueness.

5 "Perfectly clear and as vivid as normal vision

4 “Clear and reasonably vivid"

3 "Moderately clear and vivid"

2 "Vague and dim"

1 "No image at all, you only 'know' that you are thinking of an object"

7. Clouds. A storm blows up, with flashes of lightning.

5 "Perfectly clear and as vivid as normal vision

4 “Clear and reasonably vivid"

3 "Moderately clear and vivid"

2 "Vague and dim"

1 "No image at all, you only 'know' that you are thinking of an object"

8. A rainbow appears.

5 "Perfectly clear and as vivid as normal vision

4 “Clear and reasonably vivid"

3 "Moderately clear and vivid"

2 "Vague and dim"

1 "No image at all, you only 'know' that you are thinking of an object"

For items 9-12, think of **the front of a shop that you often go to**. Circle the number corresponding to the vividness of:

9. The overall appearance of the shop from the opposite side of the road.

5 "Perfectly clear and as vivid as normal vision

4 “Clear and reasonably vivid"

3 "Moderately clear and vivid"

2 "Vague and dim"

1 "No image at all, you only 'know' that you are thinking of an object"

10. A window display including colors, shape and details of individual items for sale.

5 "Perfectly clear and as vivid as normal vision

4 “Clear and reasonably vivid"

3 "Moderately clear and vivid"

2 "Vague and dim"

1 "No image at all, you only 'know' that you are thinking of an object"

11. You are near the entrance. Observe the color, shape and details of the door.

5 "Perfectly clear and as vivid as normal vision

4 “Clear and reasonably vivid"

3 "Moderately clear and vivid"

2 "Vague and dim"

1 "No image at all, you only 'know' that you are thinking of an object"

12. You enter the shop and go to the counter. The counter assistant serves you and money changes hands.

5 "Perfectly clear and as vivid as normal vision

4 “Clear and reasonably vivid"

3 "Moderately clear and vivid"

2 "Vague and dim"

1 "No image at all, you only 'know' that you are thinking of an object"

Finally, for items 13-16, think of a **country scene which involves trees, mountains and a lake**. Circle the number corresponding to the vividness of:

13. The contours of the landscape.

5 "Perfectly clear and as vivid as normal vision

4 “Clear and reasonably vivid"

3 "Moderately clear and vivid"

2 "Vague and dim"

1 "No image at all, you only 'know' that you are thinking of an object"

14. The color and shape of the trees.

5 "Perfectly clear and as vivid as normal vision

4 “Clear and reasonably vivid"

3 "Moderately clear and vivid"

2 "Vague and dim"

1 "No image at all, you only 'know' that you are thinking of an object"

15. The color and shape of the lake.

5 "Perfectly clear and as vivid as normal vision

4 “Clear and reasonably vivid"

3 "Moderately clear and vivid"

2 "Vague and dim"

1 "No image at all, you only 'know' that you are thinking of an object"

16. A strong wind blows on the tree and on the lake causing waves

5 "Perfectly clear and as vivid as normal vision

4 “Clear and reasonably vivid"

3 "Moderately clear and vivid"

2 "Vague and dim"

1 "No image at all, you only 'know' that you are thinking of an object"

Appendix B

Multidimensional Perfectionism Scale

1. **My parents set very high standards for me.**

1	2	3	4	5
Strongly disagree				Strongly agree

2. **Organization is very important to me.**

1	2	3	4	5
Strongly disagree				Strongly agree

3. **As a child, I was punished for doing things less than perfect.**

1	2	3	4	5
Strongly disagree				Strongly agree

4. **If I do not set the highest standards for myself, I am likely to end up a second-rate person.**

1	2	3	4	5
Strongly disagree				Strongly agree

5. **My parents never tried to understand my mistakes.**

1	2	3	4	5
Strongly disagree				Strongly agree

6. It is important to me that I be thoroughly competent in everything I do.

1 2 3 4 5

Strongly disagree Strongly agree

7. I am a neat person.

1 2 3 4 5

Strongly disagree Strongly agree

8. I try to be an organized person.

1 2 3 4 5

Strongly disagree Strongly agree

9. If I fail at work/school, I am a failure as a person.

1 2 3 4 5

Strongly disagree Strongly agree

10. I should be upset if I make a mistake.

1 2 3 4 5

Strongly disagree Strongly agree

11. My parents wanted me to be the best at everything.

1 2 3 4 5

Strongly disagree Strongly agree

12. I set higher goals than most people.

1 2 3 4 5

Strongly disagree Strongly agree

13. If someone does a task at work/school better than I, then I feel like I failed the whole task.

1 2 3 4 5

Strongly disagree Strongly agree

14. If I fail partly, it is as bad as being a complete failure.

1 2 3 4 5

Strongly disagree Strongly agree

15. Only outstanding performance is good enough in my family.

1 2 3 4 5

Strongly disagree Strongly agree

16. I am very good at focusing my efforts on attaining a goal.

1 2 3 4 5

Strongly disagree Strongly agree

17. Even when I do something very carefully, I often feel that it is not quite right.

1 2 3 4 5

Strongly disagree Strongly agree

18. I hate being less than the best at things.

1 2 3 4 5

Strongly disagree Strongly agree

19. I have extremely high goals.

1 2 3 4 5

Strongly disagree Strongly agree

20. My parents have expected excellence from me.

1 2 3 4 5

Strongly disagree Strongly agree

21. People will probably think less of me if I make a mistake.

1 2 3 4 5

Strongly disagree Strongly agree

22. I never felt like I could meet my parents' expectations.

1 2 3 4 5

Strongly disagree Strongly agree

23. If I do not do as well as other people, it means I am an inferior human being.

1 2 3 4 5

Strongly disagree Strongly agree

24. Other people seem to accept lower standards from themselves than I do.

1 2 3 4 5

Strongly disagree Strongly agree

25. If I do not do well all the time, people will not respect me.

1 2 3 4 5

Strongly disagree Strongly agree

26. My parents have always had higher expectations for my future than I have.

1 2 3 4 5

Strongly disagree Strongly agree

27. I try to be a neat person.

1 2 3 4 5

Strongly disagree Strongly agree

28. I usually have doubts about the simple everyday things I do.

1 2 3 4 5

Strongly disagree Strongly agree

29. Neatness is very important to me.

1 2 3 4 5

Strongly disagree Strongly agree

30. I expect higher performance in my daily tasks than most people.

1 2 3 4 5

Strongly disagree Strongly agree

31. I am an organized person.

1 2 3 4 5

Strongly disagree Strongly agree

32. I tend to get behind in my work because I repeat things over and over.

1 2 3 4 5

Strongly disagree Strongly agree

33. It takes me a long time to do something "right."

1 2 3 4 5

Strongly disagree Strongly agree

34. The fewer mistakes I make, the more people will like me.

1 2 3 4 5

Strongly disagree Strongly agree

35. I never felt like I could meet my parents' standards,

1 2 3 4 5

Strongly disagree Strongly agree

Appendix C

Object-Spatial Imagery Questionnaire

1. **I was very good in 3-D geometry as a student.**

1 2 3 4 5

Strongly disagree Strongly agree

2. **If I were asked to choose between engineering professions and visual arts, I would prefer engineering.**

1 2 3 4 5

Strongly disagree Strongly agree

3. **Architecture interests me more than painting.**

1 2 3 4 5

Strongly disagree Strongly agree

4. **My images are very colorful and bright.**

1 2 3 4 5

Strongly disagree Strongly agree

5. **I prefer schematic diagrams and sketches when reading a textbook instead of colorful and pictorial illustrations.**

1 2 3 4 5

Strongly disagree Strongly agree

6. **My images are more like schematic representations of things and events rather than detailed pictures.**

1 2 3 4 5

Strongly disagree Strongly agree

7. **When reading fiction, I usually form a clear and detailed mental picture of a scene or room that has been described.**

1 2 3 4 5

Strongly disagree Strongly agree

8. **I have a photographic memory.**

1 2 3 4 5

Strongly disagree Strongly agree

9. **I can easily imagine and mentally rotate 3-dimensional geometric figures.**

1 2 3 4 5

Strongly disagree Strongly agree

10. **When entering a familiar store to get a specific item, I can easily picture the exact location of the target item, the shelf it stands on, how it is arranged and the surrounding articles.**

1 2 3 4 5

Strongly disagree Strongly agree

11. **I normally do not experience many spontaneous vivid images; I use my mental imagery mostly when attempting to solve some problems like the ones in mathematics.**

1 2 3 4 5

Strongly disagree Strongly agree

12. My images are very vivid and photographic.

1	2	3	4	5
Strongly disagree				Strongly agree

13. I can easily sketch a blueprint for a building that I am familiar with.

1	2	3	4	5
Strongly disagree				Strongly agree

14. I am a good Tetris player.

1	2	3	4	5
Strongly disagree				Strongly agree

15. If I were asked to choose between studying architecture and visual arts, I would choose visual arts.

1	2	3	4	5
Strongly disagree				Strongly agree

16. My mental images of different objects very much resemble the size, shape and color of actual objects that I have seen.

1	2	3	4	5
Strongly disagree				Strongly agree

17. When I imagine the face of a friend, I have a perfectly clear and bright image.

1	2	3	4	5
Strongly disagree				Strongly agree

18. **I have excellent abilities in technical graphics.**

1	2	3	4	5
Strongly disagree				Strongly agree

19. **I can easily remember a great deal of visual details that someone else might never notice. For example, I would just automatically take some things in, like what color is a shirt someone wears or what color are his/her shoes.**

1	2	3	4	5
Strongly disagree				Strongly agree

20. **In high school, I had less difficulty with geometry than with art.**

1	2	3	4	5
Strongly disagree				Strongly agree

21. **I enjoy pictures with bright colors and unusual shapes like the ones in modern art.**

1	2	3	4	5
Strongly disagree				Strongly agree

22. **Sometimes my images are so vivid and persistent that it is difficult to ignore them.**

1	2	3	4	5
Strongly disagree				Strongly agree

23. When thinking about an abstract concept (e.g. ‘a building’) I imagine an abstract schematic building in my mind or its blueprint rather than a specific concrete building.

1 2 3 4 5

Strongly disagree Strongly agree

24. My images are more schematic than colorful and pictorial.

1 2 3 4 5

Strongly disagree Strongly agree

25. I can close my eyes and easily picture a scene that I have experienced.

1 2 3 4 5

Strongly disagree Strongly agree

26. I remember everything visually. I can recount what people wore to a dinner and I can talk about the way they sat and the way they looked probably in more detail than I could discuss what they said.

1 2 3 4 5

Strongly disagree Strongly agree

27. I find it difficult to imagine how a 3-dimensional geometric figure would exactly look like when rotated.

1 2 3 4 5

Strongly disagree Strongly agree

28. My visual images are in my head all the time. They are just right there.

1	2	3	4	5

Strongly disagree Strongly agree

29. My graphic abilities would make a career in architecture relatively easy for me.

1	2	3	4	5

Strongly disagree Strongly agree

30. When I hear a radio announcer or a DJ I've never actually seen, I usually find myself picturing what he or she might look like.

1	2	3	4	5

Strongly disagree Strongly agree