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Short-term storage capacity for visual objects depends on expertise

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ABSTRACT

Visual short-term memory (VSTM) has traditionally been thought to have a very limited capacity of around 3–4 objects. However, recently several researchers have argued that VSTM may be limited in the amount of information retained rather than by a specific number of objects. Here we present a study of the effect of long-term practice on VSTM capacity. We investigated four age groups ranging from pre-school children to adults and measured the change in VSTM capacity for letters and pictures. We found a clear increase in VSTM capacity for letters with age but not for pictures. Our results indicate that VSTM capacity is dependent on the level of expertise for specific types of stimuli.

1. Introduction

Visual short-term memory (VSTM) is usually described as a mechanism comprising a limited number of available memory slots to which objects may be encoded (e.g. Cattell, 1886; Luck & Vogel, 1997; Shibuya & Bundesen, 1988; Sperling, 1960; Woodman, Vogel, & Luck, 2001). The estimated capacity limitations have varied between different studies usually from three to seven objects (James, 1890); nevertheless, a consensus has been reached within the last two decades suggesting that the capacity of VSTM is approximately three to four objects at any given moment in time (Cowan, 2001). This limitation in VSTM capacity is generally assumed to be stable over time (Bundesen, 1990; James, 1890) and fully developed from very early childhood (Ross-Sheehy, Oakes, & Luck, 2003).

In the literature, VSTM is often treated synonymously with visual working memory (VWM) even where authors are using the same general paradigm (cf. Luck & Vogel, 1997; Todd & Marois, 2004). Few researchers have tried to disentangle the concepts of VSTM and VWM, but one such attempt has been made by Cowan (2008). He suggested that VSTM reflects activations in visual long-term memory (VLTM) that are currently active and VWM is the subset of these activations captured by attention and thus available for conscious report. In many respects our view is similar to that of Cowan in regard to the notion that VSTM reflects the active representations in VLTM, nevertheless, we are hesitant to use the term VWM. Here we choose to use VSTM where the measure of capacity (K) reflects the items that are currently encoded and at the same time available for conscious report (cf. Bundesen, 1990).

Some studies have questioned whether the notion of a fixed number of slots is an accurate description of VSTM; Bays and Husain (2008) have suggested a shared resource model of VSTM and along similar lines Alvarez and Cavanagh (2004) and Eng, Chen, and Jiang (2005) have proposed that memory capacity is affected by the complexity of the stimuli or the total amount of information of the individual objects rather than a fixed number of slots per se. The debate is ongoing with Awh, Barton, and Vogel (2007) arguing that the complexity account is confounded by stimulus similarity. Zhang and Luck (2009, 2008) have perhaps presented some of the strongest arguments for the object based notion of slots that either hold information about an object or lose the object altogether. Whether VSTM is best defined as a fixed number of available slots or as a more flexible processing seems to warrant more research, however, one line of inquiry could be whether an object always have the same extent, or whether objects should be regarded as more flexible entities that do not necessarily fit the standard slot based model.

Curby and Gauthier (2007) have shown that it is possible to encode a larger number of objects within some categories (e.g. faces) compared to objects of other categories (e.g. watches or cars). An effect of expertise or expertise of the specific stimulus types has also been reported suggesting that extensive training can increase the number of objects that is possible to be retained in VSTM (Sørensen, 2007). Similar results showing an increase in the capacity of VSTM dependent on the individual level of training or object expertise have also been reported between groups of car experts and novices (Curby, Glazek, & Gauthier, 2009).

Here, we present an experiment investigating how prolonged training based on differences in levels of expertise between groups has on the capacity limitations of VSTM. Previous studies investigating the effect of training on VSTM capacity concluded that training does

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not enhance capacity (Alvarez & Cavanagh, 2004; Chen, Eng, & Jiang, 2006; Olson & Jiang, 2004; Olson, Jiang, & Moore, 2005), although training affects other parameters like search rates and general task performance (Alvarez & Cavanagh, 2004). However, two aspects seem to question these results: First, the extent of the training as described may have been insufficient for changing the participants' level of expertise to becoming an expert in the use of the stimulus material. Secondly, one may be concerned whether the motivation of the participants was sufficient to establish the necessary level of expertise for effects on VSTM capacity to emerge (e.g. Curby & Gauthier, 2007; Curby et al., 2009; Sørensen, 2007). In other words, training a skillset that can be directly applied (e.g. gaining new language proficiency) may be more pertinent for an observer compared to learning to distinguish between different arbitrary experimental stimuli, which are only relevant in a very limited test set-up. To account for these concerns, we investigated the development of reading skills in normal participants; a type of training that is both extensive and highly relevant for a person who is learning to read and write.

2. Experiment

We compared the VSTM capacity for simple pictures or line drawings with VSTM for letters across different age groups. The four groups of participants that were tested were all fluent in Danish, ranging from pre-school children with little or no knowledge of letters to adults with several years of training.

Because one of the experimental stimulus categories was unknown/ or only vaguely known to some of the participants (i.e. letters for the pre-school children) a change detection paradigm (Pashler, 1988; Phillips, 1974) was used rather than a whole report paradigm (Sperling, 1960). Estimates of VSTM capacity in the change detection paradigm have more variance than in the whole report paradigm (Cusack, Lehmann, Veldsman, & Mitchell, 2009; Kyllingsbæk & Bundesen, 2009), nevertheless, change detection seems to be a valid choice of paradigm when dealing with stimulus categories that are not familiar to the test participants (Sørensen, 2010).

2.1. Method

2.1.1. Apparatus

The experiment ran in E-prime (Schneider, Eschman, & Zuccolotto, 2002). The stimuli were presented on a CRT running at 60 Hz controlled by a PC.

2.1.2. Participants

Four different age groups were recruited; pre-school children (age 6, $N=7$), 2nd grade children (age 8, $N=6$), 4th grade children (age 10, $N=7$), and adults with a mean age of 27 ($N=6$). The children were recruited from different classes within the same elementary school. Participants or their legal guardians gave informed consent and were allowed to discontinue the experiment at any time.

2.1.3. Stimulus material

Two stimulus sets were used: letters and pictures. In the letter condition, 26 different letters from the Danish alphabet [A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, R, S, T, U, V, X, Y, Z, Æ, Ø] printed in the MS LineDraw font were used and in the picture condition a set of 26 standardized line drawings from the Snodgrass and Vanderwart (1980) picture set was used. Contrary to Alvarez and Cavanagh (2004), the pictures chosen were fairly common objects that did not have a high element of similarity [Duck, Anchor, Banana, Flower, Glasses, Fish, Frog, Carrot, Hammer, Rooster, Glove, Hat, Horn, Cat, Lobster, Ruler, Umbrella, Revolver, Turtle, Tie, Bow, Mushroom, Swan, Clock, Violin] thus avoiding confounds of confusability (see Awh et al., 2007). In each trial, the stimuli were randomly sampled without replacement from the selection of 26 different letters (or pictures depending on the condition). Viewing distance to the screen was adjusted to compensate for different screen sizes, so that the radius of each stimulus object measured approximately 1.4° of visual angle. The stimuli were presented on the periphery of an imaginary circle with a radius of 6.5° around a central fixation point.

2.1.4. Procedure

After fixating the fixation cross in the middle of the screen, the participant initiated each trial by pressing the space bar on the computer keyboard. After a delay of 500 ms, the stimulus display appeared. The number of items presented in the display varied between 2, 4, 6, and 8 objects with a fixed exposure duration of 500 ms. The stimulus display was followed by a retention period of 3000 ms where only the fixation cross remained visible on the screen. Then a probe display was shown; in half of the trials the probe display would be identical with the stimulus display and in the other half of the trials one of the items from the stimulus display would be exchanged for a new item. Participants answered "no change" by pressing "1" on the keyboard or "change" by pressing "2" on the keyboard.

2.1.5. Design

The order of stimulus conditions (letters or pictures) was counter balanced across participants within each age group. 16 repetitions were conducted within each of the display sizes yielding a total of 64 trials within each condition. Before the actual experiment, the participants were familiarized with the stimuli in a short practice experiment. The practice experiment was a short version of the final experiment where the observers could familiarize themselves with the experiment before the real test. Here observers in general did approximately five trials in each of the conditions which were not included in the analysis. The individual observer indicated when they were familiar with the procedure and then continued to the real experiment.

2.2. Results

For each participant, the VSTM capacity, K, was estimated in the two stimulus conditions by fitting the data to Pashler's (1988) formula using the hit and false alarm rates of the observers:

$$K = N \times \left(\frac{Hit - FA}{1 - FA}\right),$$

where N is the number of items to be remembered, Hit and FA are the observed hits and false alarm rates from the individual participants. The mean K values were calculated for each condition within the different groups. The results are shown in Fig. 1.

In the picture condition, the average K value was 1.90 (SD = 0.74) in preschool children, 2.28 (SD = 0.81) in 2nd grade children, 2.28 (SD = 0.61) in 4th grade children, and 2.27 (SD = 0.45) in adult participants. Thus, VSTM capacity for pictures did not vary much with age.

In the critical letter condition, however, K gradually improved with age; average K value in the letter condition was measured to be 1.99 (SD = 1.10) in preschool children, 3.12 (SD = 0.49) in 2nd grade children, 3.56 (SD = 0.72) in 4th grade children and 3.88 (SD = 0.72) in adult participants (Fig. 2).

This interpretation was supported by a two-way ANOVA with condition (letters and pictures) as within participants factor and age groups (preschool, 2nd grade, 4th grade, and adults) as between participants factor showing a significant main effect of condition ($F(1,22) = 25.340$, $p < .001$, $\eta^2 = .535$, observed power = .998) and a significant interaction between condition and age group ($F(3,22) = 3.108$, $p = .047$, $\eta^2 = .298$, observed power = .642). A paired t-test within each of the age groups showed no difference ($t(6) = .202$, $p = .847$, two-tailed, $d = .068$) between the two conditions in the youngest age group, a trend towards a difference in the 2nd grade participants ($t(5) = 2.444$,

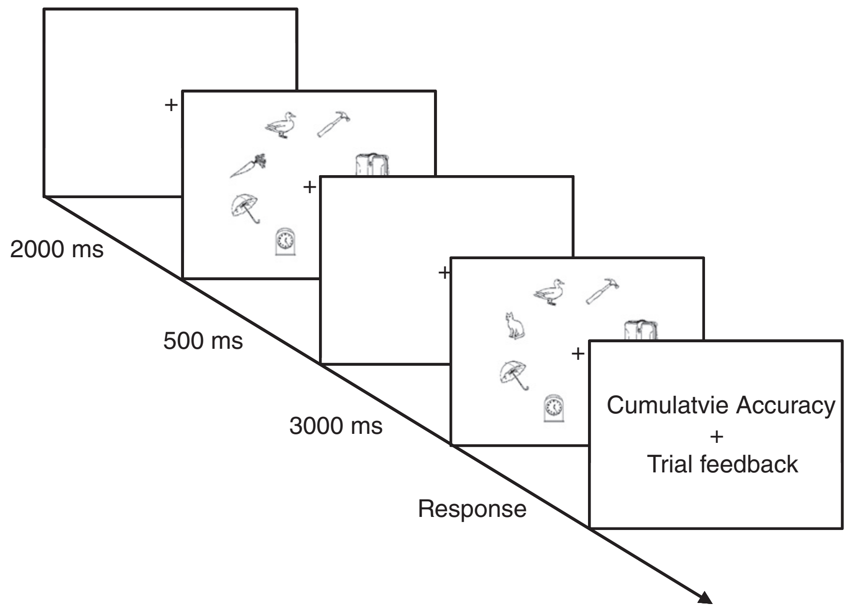

Fig. 1. Schematic illustration of the procedure used in the individual trails of the experiment; here exemplified by a “change” trial with display size of eight from the picture condition.

$p=.058$, two-tailed, $d=.887$), and finally a significant difference in both the 4th grade ($t(6)=4.192$, $p<.01$, two-tailed, $d=1.356$) and the adult ($t(5)=4.037$, $p<.05$, two-tailed, $d=1.896$) groups of observers.

Furthermore, we also compared groups within each of the two conditions and found no effect between groups in the picture condition, whereas there was an effect between groups in the letter condition summarized in Table 1 below.

Based on the data provided in the supplementary data of Alvarez and Cavanagh (2004) we performed an analysis of power between the category letters and picture they used. The analysis was made using a similar analysis as applied in the present study. A power of 0.870 was obtained. Since the present study used a selection of pictures that did not seem to have the same confusability as the pictures used in the Alvarez and Cavanagh's study, we also performed a power analysis on the two conditions in the standard adult group of the experiment and obtained a power of 0.955. Power was analyzed using G*Power (Faul, Erdfelder, Buchner, & Lang, 2009). Based on this power a group size of 6 should be sufficient.

In addition to the estimates of VSTM capacity across all display sizes, we also estimated *K* for each display size. The results were variable due to the relative small number of trial per condition, but a general decrease in *K* was found as a function of display size for letter stimuli only (cf. Cusack et al., 2009). This pattern of results was seen for all age groups.

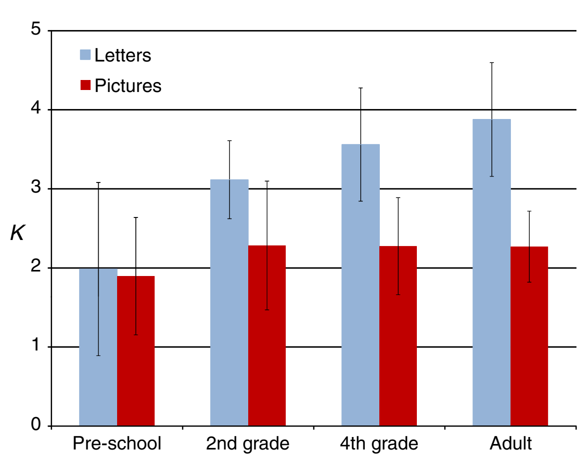

Fig. 2. *K* for letters and pictures over four groups ranging from pre-school children to adults. Error bars display the standard deviations.

2.3. Control for phonological suppression

The change detection paradigm is usually not applied to younger age groups and we did not want to make the task more complicated by introducing phonological suppression. We therefore decided to do a separate control experiment. This was conducted in a group of adult participants because we assume that this age group is best at transferring visual letters into a verbal code. The control experiment tested whether participants were able to recode visually presented information into the auditory modality thus confounding our results. A group of 12 adult participants was tested. The experiment was divided into two conditions; one condition wherein participants performed a verbal suppression task during each individual trial (Baddeley, Lewis, & Vallar, 1984, p. 243, Experiment 4) and a second condition in which the participants performed the change detection task without verbal suppression. Each condition was divided into two different blocks; one using the line-drawings as stimuli and the other using letters. Based on the difference scores (non-suppression − suppression), no significant effects where found neither for the letter condition ($t(11)=-0.675$, $p=.514$) nor for the condition using pictures ($t(11)=1.395$, $p=.191$).

These results support previous findings establishing that the change detection paradigm used here is a pure measure of VSTM capacity

Table 1
Show a comparison between groups in each of the two conditions. Significant *t*-values are marked $^{*}p<.05$, $^{**}p<.01$, and $^{***}p<.005$.

		2nd grade		4th grade		Adult	
		t	Sig.	t	Sig.	t	Sig.
Letters	Preschool	−2.454	.038*	−3.183	.009**	−3.726	.004***
	2nd grade			−1.317	.216	−2.137	.062
	4th grade					−0.794	.445
Pictures	Preschool	−0.891	.393	−1.039	.320	−1.112	.292
	2nd grade			0.22	.983	0.039	.970
	4th grade					0.019	.985

and not confounded by auditory/articulatory memory processes (Luck & Vogel, 1997; Wheeler & Treisman, 2002).

3. Discussion

We found a clear difference in the development of VSTM capacity for the two different types of stimulus material tested in our experiment. In the picture conditions, VSTM capacity was constant at around two items across the different age groups. In contrast, prolonged training in reading and writing leads to differences in the level of expertise that seem to steadily increase VSTM capacity for letters measured across the age groups. VSTM rose from two items in the group of pre-school children to about four items in the group of adult participants.

One may be concerned, that the encoding time of the line-drawing stimulus used in our study may have limited the number of encoded items, thus underestimating the VSTM capacity for pictures across the four age groups (e.g. Curby & Gauthier, 2007; Eng et al., 2005). We find this unlikely given the results reported by Alvarez and Cavanagh (2004, p. 109). In a control study, they found that cube stimuli that had the slowest processing rate of 127 ms/item reach a maximum accuracy at 450 ms and did not improve for any longer presentations up to 850 ms. Given that the processing rate of Snodgrass and Vanderwart's (1980) line-drawings also used in Alvarez and Cavanagh (2004) was much faster at about 25 ms/item, the encoding time of 500 ms used in the present study should be sufficient to preclude underestimation of the VSTM capacity of the participants.

When comparing our results to the VSTM estimates for letters and line-drawings found by Alvarez and Cavanagh (2004), we wish to note that Alvarez and Cavanagh did not apply Pashler's (1988) correction for guessing that we use in our analyses. However in the supplementary of their article (see http://www.blackwellpublishing.com/products/journals/suppmat/alvarez/alvarez_appendix.html), Alvarez and Cavanagh provide an analysis of the mean K estimates using Pashler's formula. For letters and the line-drawing category this makes a large difference: Using the model they describe in the paper $K=3.25$ and $K=3.06$ for line-drawings and letters, respectively. When using Pashler's formula, the same estimates were very different $K=2.63$ and $K=3.65$, respectively. These estimates are incidentally closer to the estimates we obtained (see also Rouder, Morey, Morey, & Cowan, 2011).

A developmental change in working memory (WM) capacity is well documented (e.g. Dempster, 1981), but usually the developmental change is reported in the auditory or phonological sub-systems of working memory (e.g. Gathercole, 1999; Huttenlocher & Burke, 1976; Jacobs, 1877). Recently, several studies have presented empirical evidence along similar lines within the visual domain (e.g. Cowan, AuBuchon, Gilchrist, Ricker, & Saults, 2011; Cowan, Morey, AuBuchon, Zwilling, & Gilchrist, 2010) and argued for a developmental change in VSTM capacity. Nevertheless, it is difficult to disentangle the nature of the developmental effect; whether the effects are due to training, general maturation, or a combination of both? By using two stimulus sets it is possible to tease out expertise through training, from maturation; in one condition (letters) groups differ in the amount of overt trained they have been exposed to, and the other (pictures) is assumed to be well established already in the youngest age group and not trained significantly afterwards. Thus, if K for letters increases with age as K for pictures remains stable (Fig. 3a) it indicates that the improvement is due to cognitive training and establishing of mental categories because of training in reading and writing. Should the developmental effect be due to a general maturation it would presumably affect K in both conditions (Fig. 3b). Finally, it is also possible that the effect is both due to training and maturation, if this is the case an increase would be predicted, however, as groups gain expertise with letters across age groups K for letters should show a relative larger increase than K for pictures (Fig. 3c).

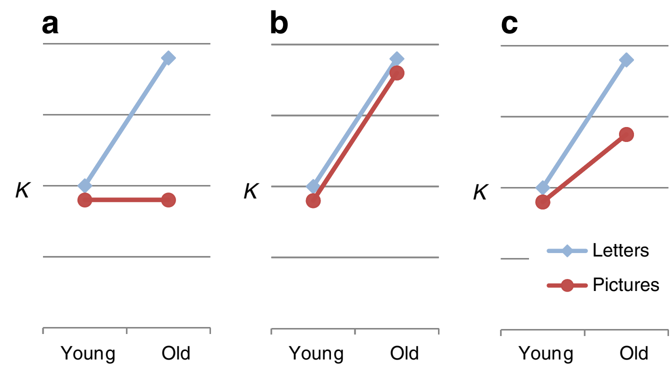

Fig. 3. Cartoon illustration of different data outcomes of the developmental effect on VSTM using the two conditions; different levels of expertise (letters, diamonds) and similar expertise levels (pictures, circles).

In the present study, we use two conditions; one (letters) in which there is explicit differences in the levels of expertise based on the amount of training between the different age groups, and another (pictures) that the participants were not familiar with prior to the experiment. The line drawings represent everyday categories (e.g. a cat, a glove, a clock); however, there is no reason to believe that these categories are trained differently across the age groups since they are assumed to be established even in the youngest children, thus the level of expertise can be assumed constant. Furthermore, some studies have argued that training is category specific with little transfer effects (see Owen et al., 2010). This suggests that an observer would have to train a specific set of stimuli like those of Snodgrass and Vanderwart's (1980) before any measurable effect on VTSM capacity would present itself. Hereby, the picture condition forms a comparison baseline with the overt expertise differences between the age groups in the letter condition.

Comparing our results from the experiment with the three different predictions of Fig. 3 we can conclude that differences in the levels of expertise based on extensive training may influence VSTM capacity significantly, contrary to previous reports (Alvarez & Cavanagh, 2004; Chen et al., 2006; Olson & Jiang, 2004). A major difference between these studies and the results presented here is the amount of training and the motivation of the tested participants. Gaining expertise in reading a language demands extensive training that is very difficult to replicate in a laboratory setting using novel nonsense objects as stimulus material. Furthermore, there may be large motivational differences for the test participants; when learning to read a language they receive a skill which will benefit their everyday life whereas learning to discriminate between types of novel stimuli has very limited relevance outside of the laboratory setting.

Gaining expertise with a specific category will likely effect representations in visual long-term memory (VLTM), but how does this result in an increase in VSTM capacity? The Neural Theory of Visual Attention of Bundesen, Habekost, and Kyllingsbæk (2005) claims that VSTM is represented by Hebb (1949) like *feedback loops* to representations in VLTM rather than fixed memory slots (see Dyrholm, Kyllingsbæk, Espeseth, & Bundesen, 2011). Information from a limited number of visual objects is retained in VSTM by reverberating activation originating from a VSTM map that holds pointers to about four items (see also Usher & Cohen, 1999). We may therefore effectively be measuring a variable number of objects in VSTM, but this measure is restricted by the resolution of the objects that in turn is represented by the number and quality of the feedback loops, which may vary from object to object. Within this framework, the quality of the representations in VLTM will also affect the capacity of VSTM. The strength and thus the stability of the feedback loops will be dependent both on the strength of the activation coming from the pointers in the VSTM map and on the strength of the reverberating activation returning from representations in VLTM. If the representations in VLTM are poor or limited in number, the resulting feedback loops will be fragile. Thus, information of these types of representations will have a higher probability of being lost from VSTM. In contrast, numerous and strong representations in VLTM will promote strong and efficient feedback loops. Thus, as categorical representations are strengthened through rigorous training and elevated levels of expertise, VLTM representations will be more specific and greater in numbers resulting in higher measures of VSTM capacity.

In future studies it would be important to further investigate the reported effect with a higher emphasis on control of stimulus complexity, to see if performance between different age groups on pseudo letters would be similar to the performance reported here on the line-drawings. Moreover, it would also be prudent to make longitudinal investigations in groups of participants. This would enable stronger conclusions about the influence of training and expertise on VSTM capacity.

4. Conclusion

We have demonstrated a measurable difference in VSTM capacity, K, between two different conditions (letters and pictures) over four different age groups (from preschoolers to adults). Developmental differences in working memory are well documented (e.g. Dempster, 1981), however, this effect is typically demonstrated in studies of span especially within the auditory domain. VSTM on the other hand usually presents a capacity limitation of around 3–4 objects irrespective of development; from 1-year old children (e.g. Ross-Sheehy et al., 2003) to adult observers (e.g. Luck & Vogel, 1997). We find in one condition (pictures) that K remains stable in around two objects over the age groups tested, which is difficult to reconcile with the notion that K is 3–4 objects independent of type or category (as argued by Awh et al., 2007; Luck & Vogel, 1997) and seems to warrant further investigations into the nature of what constitutes a visual object. Furthermore, a developmental effect is reported between age groups in a second condition (letters). Contrary to Ross-Sheehy et al. (2003) we find a capacity limitation of around two objects in our youngest age group and hereafter a steady increase to adult performance of approximately four objects. Developmental effects may both be due to the effects of expertise and general development of the cognitive architecture. Nevertheless, we found that only the condition where observers explicitly have different levels of expertise (letters) shows an increase in K while the other condition (pictures) remains stable over age groups, the parsimonious explanation is that the reported effect is due to expertise rather than to a general maturation. Our results suggests that VSTM can be affected by the expertise of the visual categories by the observer (see also Curby et al., 2009) thus challenging previous reports of the seemingly stable nature of the capacity of VSTM.

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References

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*, 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.

Baddeley, A. D., Lewis, V. J., & Vallar, G. (1984). Exploring the articulatory loop. *Quarterly Journal of Experimental Psychology*, *36*, 233–252.

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

Bundesen, C. (1990). A theory of visual attention. *Psychological Review*, *97*, 523–547.

Bundesen, C., Habekost, T., & Kyllingsbæk, S. (2005). A neural theory of visual attention. Bridging cognition and neurophysiology. *Psychological Review*, *112*, 291–328.

Cattell, J. M. (1886). The inertia of the eye and brain. *Brain*, *8*, 295–312.

Chen, D., Eng, H. Y., & Jiang, Y. (2006). Visual working memory for trained and novel polygons. *Visual Cognition*, *14*, 37–54.

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

Cowan, N. (2008). What are the differences between long-term, short-term, and working memory? In W. S. Sossin, J. -C. Lacaille, V. F. Castellucci, & S. Belleville (Eds.), *Progress in brain research*, *vol. 169*.

Cowan, N., AuBuchon, A. M., Gilchrist, A. L., Ricker, T. J., & Saults, J. S. (2011). Age differences in visual working memory capacity: Not based on encoding limitations. *Developmental Science*, 1–9.

Cowan, N., Morey, C. C., AuBuchon, A. M., Zwilling, C. E., & Gilchrist, A. L. (2010). Seven-year-olds allocate attention like adults unless working memory is overloaded. *Developmental Science*, *13*, 120–133.

Curby, K. M., & Gauthier, I. (2007). A visual short-term memory advantage for faces. *Psychonomic Bulletin & Review*, *14*, 620–628.

Curby, K. M., Glazek, K., & Gauthier, I. (2009). A visual short-term memory advantage for objects of expertise. *Journal of Experimental Psychology. Human Perception and Performance*, *35*, 94–107.

Cusack, R., Lehmann, M., Veldsman, M., & Mitchell, D. J. (2009). Encoding strategy and not visual working memory capacity correlates with intelligence. *Psychonomic Bulletin & Review*, *16*, 641–647.

Dempster, F. N. (1981). Memory span: Sources of individual and developmental differences. *Psychological Bulletin*, *89*, 63–100.

Dyrholm, M., Kyllingsbæk, S., Espeseth, T., & Bundesen, C. (2011). Generalizing parametric models by introducing trial-by-trial parameter variability: The case of TVA. *Journal of Mathematical Psychology*, *55*, 416–429.

Eng, H. Y., Chen, D., & Jiang, Y. (2005). Visual working memory for simple and complex visual stimuli. *Psychonomic Bulletin & Review*, *12*, 1127–1133.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, *41*, 1149–1160.

Gathercole, S. E. (1999). Cognitive approaches to the development of short-term memory. *Trends in Cognitive Science*, *3*, 410–419.

Hebb, D. O. (1949). *The organization of behavior: A neuropsychological theory*. New York: Wiley.

Huttenlocher, J., & Burke, D. (1976). Why does memory span increase with age? *Cognitive Psychology*, *8*, 1–31.

Jacobs, J. (1877). Experiments on “prehension”. *Mind*, *12*, 75–79.

James, W. (1890). *The principles of psychology*. : Dover Publications.

Kyllingsbæk, S., & Bundesen, C. (2009). Changing change detection: Improving the reliability of measures of visual short-term memory capacity. *Psychonomic Bulletin & Review*, *16*, 1000–1010.

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

Olson, I. R., & Jiang, Y. (2004). Visual short-term memory is not improved by training. *Memory & Cognition*, *32*, 1326–1332.

Olson, I. R., Jiang, Y., & Moore, K. S. (2005). Associative learning improves visual working memory performance. *Journal of Experimental Psychology. Human Perception and Performance*, *31*, 889–900.

Owen, A. M., Hampshire, A., Grahn, J. A., Stenton, R., Dajani, S., Burns, A. S., et al. (2010). Putting brain training to the test. *Nature*, *465*(10), 775–778.

Pashler, H. (1988). Familiarity and visual change detection. *Perception & Psychophysics*, *44*, 369–378.

Phillips, W. A. (1974). On the distinction between sensory storage and short-term visual memory. *Perception & Psychophysics*, *16*, 283–290.

Rouder, J. N., Morey, R. D., Morey, C. C., & Cowan, N. (2011). How to measure working memory capacity in the change detection paradigm. *Psychonomic Bulletin & Review*, *18*, 324–330.

Ross-Sheehy, S., Oakes, L. M., & Luck, S. J. (2003). The development of visual short-term memory capacity in infants. *Child Development*, *74*, 1807–1822.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime User's Guide*. Pittsburgh: Psychology Software Tools Inc.

Shibuya, H., & Bundesen, C. (1988). Visual selection from multielement displays: Measure and modeling effects of exposure duration. *Journal of Experimental Psychology. Human Perception and Performance*, *14*, 591–600.

Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology. Human Learning and Memory*, *6*, 174–215.

Sørensen, T. A. (2007). Visual short-term memory — Is capacity dependent on stimulus complexity? *Proceedings of the European Society for Cognitive Psychology* (pp. 99–100).

Sørensen, T. A. (2010). Stability of parameters in repeated TVA measures: Whole report versus change detection. *Meeting of the International TVA network*. http://itva.files.wordpress.com/2010/07/soerensen-2010-stability-of-parameters-in-repeated-tva-measures.pdf. Accessed June 12. 2011.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied*, *74*(11), 1–30.

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

Usher, M., & Cohen, J. D. (1999). Short term memory and selection processes in a frontal-lobe model. In D. Heinke, G. W. Humphreys, & A. Olson (Eds.), *Connectionist models in cognitive neuroscience* (pp. 78–91). Berlin, Germany: Springer-Verlag.

Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology. General*, *131*, 48–64.

Woodman, G., Vogel, E., & Luck, S. (2001). Visual search remains efficient when visual working memory is full. *Psychological Science*, *12*, 219–224.

Zhang, W., & Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature*, *453*, 233–235.

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