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Short-term storage capacity for visual objects depends on expertise

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1. Introduction

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.

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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.

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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 and were allowed to discontinue the experiment at any time.

The practice experiment was a short version of the randomized display 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.

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 (\(t(5) = 2.444\), .06).
\( p = .058, \text{two-tailed, } d = .887 \), and finally a significant difference in both the 4th grade \((t(5) = 4.037, p < .05, \text{two-tailed, } d = 1.896)\) and the adult \((t(5) = 4.192, p < .01, \text{two-tailed, } d = 1.356)\) 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.

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

<table>
<thead>
<tr>
<th></th>
<th>Letters</th>
<th></th>
<th></th>
<th>Pictures</th>
<th></th>
</tr>
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<tbody>
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<td></td>
<td>2nd grade</td>
<td>4th grade</td>
<td>Adult</td>
<td>2nd grade</td>
<td>4th grade</td>
</tr>
<tr>
<td></td>
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<td>t</td>
<td>Sig.</td>
<td>t</td>
<td>Sig.</td>
</tr>
<tr>
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<td></td>
<td>−3.183</td>
<td>.009*</td>
</tr>
<tr>
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<td>.216</td>
<td></td>
<td>−2.137</td>
<td>.062</td>
</tr>
<tr>
<td>4th grade</td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td>−0.22</td>
<td>.983</td>
</tr>
</tbody>
</table>

*Significant t-values are marked *\(p < .05\), **\(p < .01\), and ***\(p < .005\).*

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

Fig. 2. \( K \) for letters and pictures over four groups ranging from pre-school children to adults. Error bars display the standard deviations.
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/support/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, & Sauls, 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).

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 VSTM 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 VSTM. If the representations in VSTM 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 VSTM will promote strong and efficient feedback loops. Thus, as categorical representations are strengthened through rigorous training and elevated levels of expertise, VSTM 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 thereafter 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 suggest 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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