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The impact of visual working memory capacity on the filtering efficiency of emotional face distractors

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Running title: VWM capacity affects face distractor filtering

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Abstract

Emotional faces can serve as distractors for visual working memory (VWM) tasks. An event-related potential called contralateral delay activity (CDA) can measure the filtering efficiency of face distractors. Previous studies have investigated the influence of VWM capacity on filtering efficiency of simple neutral distractors but not of face distractors. We measured the CDA indicative of emotional face filtering during a VWM task related to facial identity. VWM capacity was measured in a separate colour change detection task, and participants were divided to high- and low-capacity groups. The high-capacity group was able to filter out distractors similarly irrespective of its facial emotion. In contrast, the low-capacity group failed in filtering the neutral and angry face distractors, while the filtering was efficient for the happy face distractors. The results indicate that potentially threatening faces are particularly difficult to filter if VWM capacity is limited.

Keywords: contralateral delay activity; distractor filtering; facial expressions; memory storage; sustained posterior contralateral negativity; visual short-term memory

1. Introduction

Humans must maintain visual contents in a temporary storage buffer in order to allow for their effective processing. This mental storage system is called visual working memory (VWM). VWM allows integration of information from sensory inputs, thus enabling a dynamic and coherent visual experience. VWM representations can be mentally accessed and manipulated, even when the visual scene disappears (Cowan, 2001; Luck & Vogel, 1997). Moreover, relevant information from a visual scene can be selected by VWM for processing, and distracting information can be filtered (Vogel, McCollough, & Machizawa, 2005).

Of all the different kinds of visual information, humans are most specialised at perception of faces, and faces capture attention more efficiently than other meaningful objects (Ro, Russell, & Lavie, 2001; Vuilleumier, 2000; Young & Burton, 2018). There are different processing advantages for different emotional faces; for example, angry faces are particularly efficient at capturing our attention (Fox et al., 2000; Hansen & Hansen, 1988; Pinkham, Griffin, Baron, Sasson, & Gur, 2010). Studies of VWM have also shown that emotional expressions modulate performance of face identification. Data from behavioural studies indicated that participants could store more facial identities in VWM when the faces were angry than when they were happy or neutral, even if the facial emotions were irrelevant to the task (Jackson, Linden, & Raymond, 2014; Jackson, Wu, Linden, & Raymond, 2009). These results suggest that, compared to happy and neutral faces, angry faces can enhance storage of visual information for facial identities. However, in behavioural studies, VWM storage is difficult to study without involvement of other cognitive processes, such as memory encoding and decision-making.

In the present study, VWM for emotional faces was investigated by using a recently found event-related potential (ERP) component called contralateral delay activity (CDA; also known as sustained posterior contralateral negativity, or SPCN) which can index the number of objects maintained by VWM. Its amplitude is strongly modulated by the number of items in VWM during the maintenance phase (Feldmann-Wüstefeld, Vogel, & Awh, 2018; Gao et al., 2009; Gao et al., 2011; Vogel & Machizawa, 2004), and it reaches an asymptote once approximately three to four simple objects are stored, reflecting the limitation of individual's VWM capacity (Luria, Balaban, Awh, & Vogel, 2016). CDA has been used to index VWM storage of facial objects (Meconi, Luria, & Sessa, 2014; Sessa & Dalmaso, 2016; Sessa, Luria, Gotler, Jolicoeur, & Dell'Acqua, 2011; Sessa et al., 2012). Sessa et al. (2011) used CDA to investigate the VWM maintenance of fearful faces. Participants were asked to memorise identities of fearful or neutral faces. Their results showed that memorising the identity of a fearful face elicited larger CDA amplitude than that of a neutral face (Sessa et al., 2011). The authors suggested that participants maintained more visual information in the VWM for fearful faces compared to neutral faces.

Recently, studies on VWM for emotional faces have expanded from maintenance to distractor filtering (Stout, Shackman, Johnson, & Larson, 2015; Stout, Shackman, & Larson, 2013). Researchers have used CDA to investigate filtering efficiency of irrelevant information during VWM processing (Stout et al., 2013; Vogel et al., 2005). Stout et al. (2013) used this method to study efficiency of filtering task-irrelevant fearful faces. Participants were asked to memorise the identity of one neutral target face while ignoring a distractor (either a fearful or a neutral face). CDA amplitude was larger for the fearful distractor condition compared to the condition without a distractor (one-target condition). However, CDA amplitude did not differ between the neutral distractor condition and one-target condition (Stout et al., 2013). The results thus indicate that fearful distractors are automatically stored in VWM, even when they are irrelevant to the task, while neutral distractors are effectively filtered out of VWM. This suggests that the type of distractor itself affects filtering efficiency. Quite surprisingly, previous studies have not used CDA to investigate filtering efficiency of VWM for faces other than fearful or neutral.

Filtering efficiency of distractors is also affected by an individual's VWM capacity (Jost, Bryck, Vogel, & Mayr, 2011; Owens, Koster, & Derakshan, 2012; Vogel et al., 2005). Vogel et al. (2005) found that individuals with high and low VWM capacity differ in their efficiency at filtering irrelevant objects during VWM tasks. Participants were instructed to memorise two targets' orientations and ignore two distractors' orientations. CDA amplitude was used to examine whether irrelevant distractors unnecessarily consume VWM storage. The result suggested that participants with high VWM capacity were able to filter out the distractors, but those with low VWM capacity tended to store distractors to VWM. Cowan and Morey (2006) interpreted this result as showing that VWM depends on attentional filtering. Because VWM and selective attention share some similar neural mechanisms (Ku, 2018), this could explain why VWM capacity and filtering efficiency are interlinked. Further support has been provided by a study which showed that high-capacity individuals were more capable of resisting attentional capture than low-capacity individuals (Fukuda & Vogel, 2009).

However, although many previous studies have investigated the influence of VWM capacity on filtering efficiency of simple neutral distractor items (colours or orientations as target features, Owens et al., 2012; Vogel et al., 2005), very little is known about the impact of VWM capacity on filtering efficiency of emotional face distractors. The purpose of the present study is to provide first-hand evidence on the impact of VWM capacity on ability to filter emotional face distractors.

Because the focus of the present study is on VWM filtering efficiency rather than on maintenance efficiency, a low memory load similar to the study by Stout et al. (2013) was chosen. Participants were asked to selectively remember the identities of one or two faces while ignoring others. Angry and happy faces were used as emotional distractors because these have not been applied in previous CDA studies (Meconi et al., 2014; Sessa & Dalmaso, 2016; Sessa et al., 2011; Sessa et al., 2012; Stout et al., 2013). There were three categories of conditions in this study: one-target condition (one neutral face), two-target conditions (two neutral faces, or one neutral and one emotional face) and distractor conditions (one neutral target face and one neutral distractor face, or one neutral target face and one emotional distractor face).

Based on previous CDA studies (Vogel & Machizawa, 2004; Vogel et al., 2005), it was predicted that CDA amplitude in two-target conditions would be larger than that in the one-target condition, and CDA amplitude in distractor conditions would be between those in one-target and two-target conditions. In principle, if participants could filter out the distractors, then CDA amplitude of distractor conditions would not be different from that of one-target condition. On the contrary, if they could not filter out the distractors, then there would be no difference in CDA amplitude between distractor and two-target conditions.

The study by Vogel et al. (2005) suggested that individuals with low VWM capacity are less efficient at filtering out simple neutral distractors. Although the results related to filtering of simple neutral distractors may not necessarily be generalised to filtering of neutral face distractors, it was hypothesised that participants with low VWM capacity would be less efficient at filtering neutral face distractors than high-capacity participants.

Furthermore, because several studies have proposed that angry faces can automatically capture more attention compared to happy faces (Fox et al., 2000; Hansen & Hansen, 1988; Pinkham et al., 2010), it was hypothesised that filtering of angry face distractors would be more difficult than filtering of happy face distractors. This might be especially true for low-capacity participants because they can be assumed to be worse at resisting attentional capture by distractors (Fukuda & Vogel, 2009).

2. Method

2.1 Participants

As paid volunteers, forty-two undergraduate students (21.65 ±2.07 years old, age range 18–25 years; 2 left-handed; 10 males) were recruited from the volunteering participant pool at Liaoning Normal University in China. The inclusion criteria for participants were age of 18 years or more, self-reported normal colour vision and normal or corrected-to-normal visual acuity. Exclusion criteria were history of psychiatric disorders and previous participation in working memory experiments. Written informed consent was provided by each participant prior to the experiment. All procedures were in compliance with the Declaration of Helsinki and were approved by the ethics committee of Liaoning Normal University.

2.2 Tasks

The study consisted of two tasks: a facial VWM task followed by a VWM capacity measurement. To investigate the VWM processing of facial objects, electroencephalography (EEG) measurements with responses time-locked to the stimuli were applied while the participants conducted the facial VWM task. A colour change detection task was used as the VWM capacity measurement to quantify capacity in each participant. In order to ensure the ERP results of the facial VWM task would not be influenced by the experience of VWM capacity measurements, participants first completed the facial VWM task and then the VWM capacity measurement after a short break. Participants were seated in a sound-proof dark room at a distance of 70 cm from a 17-inch screen.

2.3 Materials

In the facial VWM task, three different types of emotional (neutral, angry and happy) facial images were used as stimuli. A previous study suggested that participants have an advantage when detecting angry expressions on male faces compared to female faces (Becker, Kenrick, Neuberg, Blackwell, & Smith, 2007). To maximise the effects of attentional capture by angry faces, only pictures of male actors were used in the experiment. A total of 54 images of male faces (18 neutral, 18 angry and 18 happy) were selected from the Chinese Facial Affective Picture System (CFAPS; Gong, Huang, Wang, & Luo, 2011). The CFAPS has been widely used to investigate human emotional face processing (Guo et al., 2013; Liu, Zhang, & Luo, 2014; Luo, Feng, He, Wang, & Luo, 2010; Tian et al., 2018; Zheng et al., 2015). In the CFAPS, all images are similar in size, background, spatial frequency, contrast grade, brightness and other physical properties. Each selected image had a high agreement rate in emotion categorisation (more than 70% agreement rate for each angry and neutral expression image and more than 90% agreement rate for each happy expression image). One-way ANOVAs were used to investigate whether valence and arousal differed between the categories of emotional faces. There was a main effect for both valence, $F(2,51) = 216.348$, $p < 0.001$ and arousal $F(2,51) = 14.307$, $p < 0.001$. Follow-up pairwise comparisons showed that the valence of neutral faces (M = 4.19, SD = 0.65) was significantly more positive than that of angry faces (M = 2.66, SD = 0.39; $p < .001$) and more negative than that of happy faces (M = 6.48, SD = 0.59; $p < .001$). The arousal of neutral faces (M = 4.44, SD = 0.46) was significantly lower than that of angry (M = 6.31, SD = 1.35; $p < .001$) and happy faces (M = 5.80, SD = 1.22; $p < .001$), but there was no significant difference in arousal between angry and happy faces ($p = .280$).

Faces were presented with a grey background and were framed with rectangular borders (2.6° wide × 3° tall). Both the memory array and test array contained facial images that were placed in fixed locations surrounding a fixation cross. Horizontal distance between the facial images and the fixation cross was 2.9°. Vertical distance between the top and bottom of faces was 1.6°.

In the VWM capacity measurement, all stimulus arrays were presented with a grey background, and they occupied a 9.8°×7.3° area (Figure 2). Each item in the stimulus array was a square (size: 0.65°×0.65°), the colour of which was selected at random without replacement from a set of seven discriminable colours (red, green, blue, orange, yellow, purple, pink). The positions of squares were randomised on each trial and were separated by at least 2°.

2.4 Experimental procedure

2.4.1 Facial VWM task

The basic trial structure was a facial lateralised change detection task adapted from the study by Stout et al. (2013). Because the consolidation of VWM representation is a coarse-to-fine process (Gao & Bentin, 2011; Gao, Ding, Yang, Liang, & Shui, 2013), relatively long exposure duration (500 ms) was used to ensure that participants could voluntarily allocate VWM resource to remember details (Ye et al., 2017). The trial structures are depicted in Figure 1a. Each trial began with a fixation cross (500 ms in duration) in the centre of the screen, followed by a pair of arrow cues (200 ms), which were displayed above and below the fixation cross, both pointing to the same direction (either to left or right). After a variable interval (200–400 ms), a memory array of two or four faces was displayed (500 ms). Following the memory array, a blank screen (900 ms) preceded the onset of the test array. The test array was exposed until participants responded. Participants were instructed to maintain fixation throughout the trial and were asked to only memorise the identity of the faces in the visual hemifield as indicated by the cues. The faces presented in the non-cued visual hemifield always maintained the same emotion as the ones in the cued hemifield. The faces were surrounded by red or yellow frames (target or distractor frames, counterbalanced across participants). Participants were asked to only memorise the identity of faces surrounded by the target frames and indicate by a button press whether there was a change in the target identity or not. Participants were explicitly informed that the emotion of the faces and the faces displayed in the non-cued visual hemifield were irrelevant for the task. The test array in the cued visual hemifield had one different face than the memory array in 50% of the trials; they were identical in the remaining trials. When a change in identity of a target occurred, the facial emotion remained the same. The change did not occur on the distractor faces or the faces in the non-cued visual hemifield. The participant’s task was to indicate whether the test array was identical to the memory array or if a target face had changed identity. Instruction emphasised response accuracy rather than response speed. Following the response, a variable interval (900–1100 ms) elapsed before the beginning of the next trial.

Examples of memory array of cued visual hemifield in each condition can be found in Figure 1b. The task included three categories of conditions: one-target condition, two-target conditions and distractor conditions. The 1 neutral target (1Nt) condition served as the baseline. Three different two-target conditions were applied in which the set size was two and only task-relevant faces were presented. The combinations were 2 neutral targets (2Nt), 1 neutral target and 1 angry target (1Nt1At) or 1 neutral target and 1 happy target (1Nt1Ht). In addition, to assess the impact of facial distractors on VWM maintenance, three different distractor conditions, neutral, angry and happy, were applied. The combinations were 1 neutral target and 1 neutral distractor (1Nt1Nd), 1 neutral target and 1 angry distractor (1Nt1Ad) or 1 neutral target and 1 happy distractor (1Nt1Hd). Consequently, there were a total of seven conditions in the facial VWM task. Participants completed 160 trials for each condition, with a total of 1120 trials organised into eight 140-trial blocks which were fully randomised. There was a 30-second break between each 140-trial block. At least 24 practice trials were given prior to recording test performance. The entire task lasted approximately 75 min.

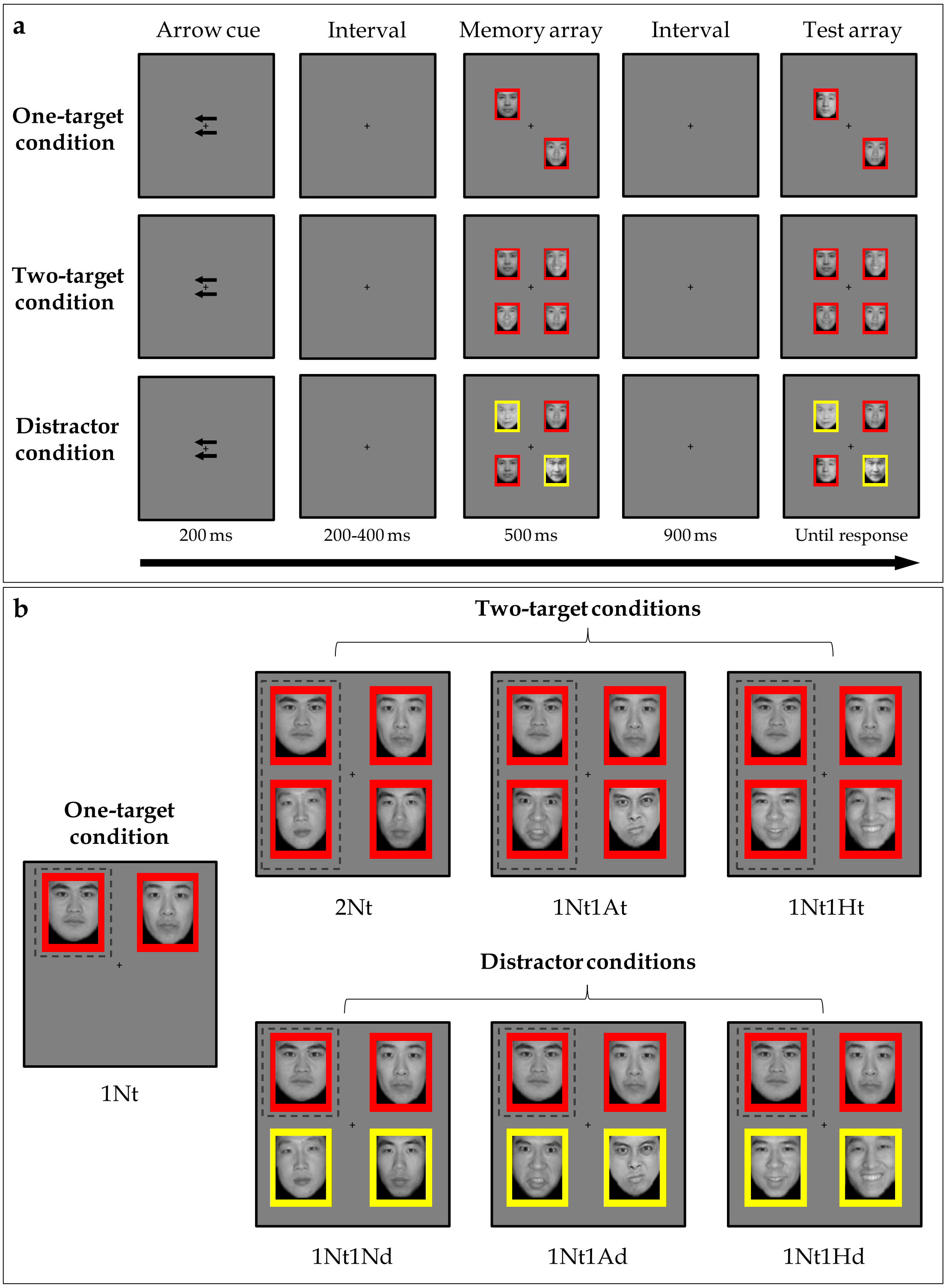

Figure 1. a) Trial structure of the VWM task and three categories of conditions. All arrow cues point to the left visual hemifield, red frame indicates targets to be memorised and yellow frame indicates distractors. Here only trials with identity changes are demonstrated. b) One example of memory array for each of seven different conditions in the trial, with arrow cues pointing to the left visual hemifield.

The dashed line is used to indicate target items and was not present during the experiment.

2.4.2 VWM capacity measurement

As a conventional paradigm, the single-probed colour change detection paradigm was used in the VWM capacity measurement (Vogel et al., 2005). The paradigm was first introduced by Phillips (1974) and popularised by Luck and Vogel (1997). As illustrated by Figure 2, each trial began with a fixation cross (500 ms), which was followed by a sample array of 6 coloured squares (200 ms). Participants were instructed to remember these coloured squares. After a blank interval (900 ms), a probe array with 1 coloured square (2500 ms) was presented. The task was to indicate whether the probe coloured was the same as the one in that specific location in the memory array, with accuracy rather than response speed being stressed. The colours within a given array were selected at random without replacement from the chosen colours. All participants completed 100 trials of this task, with a 30-second break after first 50 trials. The measurement lasted approximately 10 min.

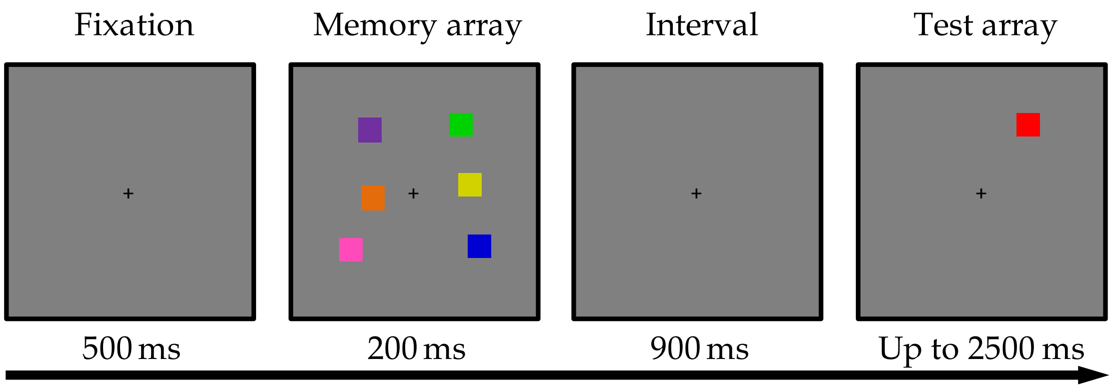

Figure 2. The trial structure of the VWM capacity measurement.

2.5 EEG recording and analysis

During the facial VWM task, EEG activity was recorded continuously using a 64-channel elastic cap. In addition to the online vertex (Cz) reference, the data were algebraically re-referenced off-line to the average of the left and right mastoids during post-recording analyses. The vertical electro-oculogram (VEOG) was recorded with a pair of bipolar-referenced electrodes, one above and one below the right eye. The horizontal electro-oculogram (HEOG) was recorded with a pair of bipolar-referenced electrodes placed laterally to the outer canthi of both eyes. Impedance at each electrode site was maintained below 5 kΩ. The EEG and EOG signals were amplified with a 50 Hz low-pass and were digitised at a sampling rate of 500 Hz.

The EEG was segmented into 1600 ms epochs starting from 200 ms before the onset of the memory array. The averaged ERP waveforms were filtered by applying a 17 Hz low-pass filter (Ye, Zhang, Liu, Li, & Liu, 2014). Epochs were baseline corrected for the 200 ms pre-stimulus interval. The trials contaminated with horizontal eye movements and reflected as HEOG amplitude greater than ±70 μV were excluded from analysis. After that, trials with remaining artefacts exceeding ±80 μV in amplitude were rejected. Participants with trial rejection rates higher than 30% were excluded from the analyses. Ten participants (all right-handed; one male) were excluded on this basis. The results reported here are thus based on data from the remaining 32 participants. The number of excluded participants was similar to previous ERP studies (Sessa et al., 2011; Stout et al., 2013).

3. Statistical Analysis

A significance level of $p < .05$ was used for all tests. Also, marginally significant ($p < .10$) results were reported. Mixed-model repeated measures ANOVA with conditions (1Nt vs. 1Nt1Nd vs. 1Nt1Ad vs. 1Nt1Hd vs. 2Nt vs. 1Nt1At vs. 1Nt1Ht) as a within-subject factor and VWM capacity group (high-capacity vs. low-capacity) as a between-subject factor were conducted for behavioural accuracy and CDA amplitude. The paired t-tests were conducted for the follow-up pairwise comparison of different emotional conditions (neutral, angry and happy) in both groups with a bootstrapping method (SPSS version 24.0; 10,000 permutations with 95% confidence intervals). Cohen's *d* was used as an estimator of the effect size for the t-tests. Two-tailed t-tests were conducted for the behavioural results. Due to a clear prediction of the difference direction in CDA amplitudes, one-tailed t-tests were conducted for these. Bayes factor analysis was used to avoid null results that were observed by chance (Rouder, Speckman, Sun, Morey, & Iverson, 2009). Bayes factor (BF_{10}) provides an odds ratio for the alternative/null hypotheses (values < 1 favour the null hypothesis and values > 1 favour the alternative hypothesis). For example, a BF_{10} of 0.25 would indicate that the null hypothesis is 4 times more likely than the alternative hypothesis.

3.1 ERP data analysis

Based on previous studies (He, Zhang, Li, & Guo, 2015; McCollough, Machizawa, & Vogel, 2007; Shen, Yu, Xu, & Gao, 2013), 4 pairs of electrodes at posterior parietal sites (P5/6, PO3/4, PO5/6, PO7/8) were chosen for analysis. For each stimulus condition, the contralateral waveforms were calculated by averaging the activity recorded at left hemisphere electrode sites when participants were cued to memorise the right side of the memory array, and with the activity recorded at right hemisphere electrode sites when they were cued to memorise the left side. The ipsilateral waveforms were computed by averaging left and right hemisphere sites when participants were cued to memorise the left and right side of the memory array, respectively. The CDA amplitude was defined by subtracting the ipsilateral activity from the contralateral activity, with a measurement window of 550–1000 ms after the onset of the memory array. Instead of choosing the time window from 500 ms, selecting this time period allowed for avoiding possible contaminations due to perceptual processing since it is successive to the disappearance of the memory array.

3.2 VWM capacity measurement analysis

Similar to studies reporting individual differences in VWM capacity (Fukuda, Mance, & Vogel, 2015; Fukuda, Vogel, Mayr, & Awh, 2010; Gaspar, Christie, Prime, Jolicoeur, & McDonald, 2016; Matsuyoshi, Osaka, & Osaka, 2014), VWM capacity of each participant was quantified based on their results in the colour change detection task. The standard formula proposed by Cowan (2001) was applied: $K_c = N(H-F)$, where K_c is VWM capacity, N is the size of the array (i.e. six in the present study), H is the hit rate or proportion of correct responses when a change is present and F is the false alarm rate or proportion of incorrect responses when no change is present. As with many previous VWM studies, participants were divided into a high-capacity group and a low-capacity group by using a median split on their K_c scores (Li, He, Wang, Hu, & Guo, 2017; Owens et al., 2012; Vogel et al., 2005; Weaver, Hickey, & van Zoest, 2017; Zhou et al., 2011).

4. Results and discussion

The median split on the K_c scores resulted in 16 participants (1 left-handed; 5 males) in the high-capacity group (M = 2.70, SD = 0.54) and 16 participants (1 left-handed; 4 males) in the low-capacity group (M = 1.54, SD = 0.34). VWM capacity differed between the groups ($p < .001$). The sample set size in each capacity group was similar to a previous study using a similar split into low- and high-capacity groups (Owens et al., 2012). No difference was found in the number of valid trials between the high- (M = 78.30%, SD = 8.76%) and low-capacity (M = 79.57%, SD = 9.40%) groups. A mixed-model repeated measures ANOVA with conditions (1Nt vs. 1Nt1Nd vs. 1Nt1Ad vs. 1Nt1Hd vs. 2Nt vs. 1Nt1At vs. 1Nt1Ht) and VWM capacity group (high-capacity vs. low-capacity) found no significant effects on the number of valid trials (all p-values > 0.154).

4.1 Behavioural results

The accuracies in each stimulus condition for the high- and low-capacity groups are shown in Figures 3a and 3b and reported in Table 1. The ANOVA showed significant main effects of condition, $F(6,180) = 125.031$, $p < .001$, $\eta^2 = 0.806$, and of VWM capacity group, $F(1,30) = 4.797$, $p < .05$, $\eta^2 = 0.179$, but no significant interaction between condition by group, $F(6,180) = 1.828$, $p = .152$, $\eta^2 = 0.057$. The accuracy of the high-capacity group (M = 0.79, SD = 0.107) was better than that of the low-capacity group (M = 0.72, SD = 0.128). The accuracy was higher in the conditions in which participants needed to memorise one target (1Nt, 1Nt1Nd, 1Nt1Ad and 1Nt1Hd) than two targets (2Nt, 1Nt1At and 1Nt1Ht; all *p*-values < .001). There was no significant difference in accuracy between 1Nt, 1Nt1Nd, 1Nt1Ad and 1Nt1Hd conditions (all *p*-values > .452). Similarly, there was no significant difference between 2Nt, 1Nt1At and 1Nt1Ht conditions (all *p*-values > .308). The results showed that memory accuracy was worse for two-target than for one-target and distractor conditions. Although the participants with high VWM capacity had better performance than the participants with low VWM capacity, the groups did not differ in their performance as a function of condition.

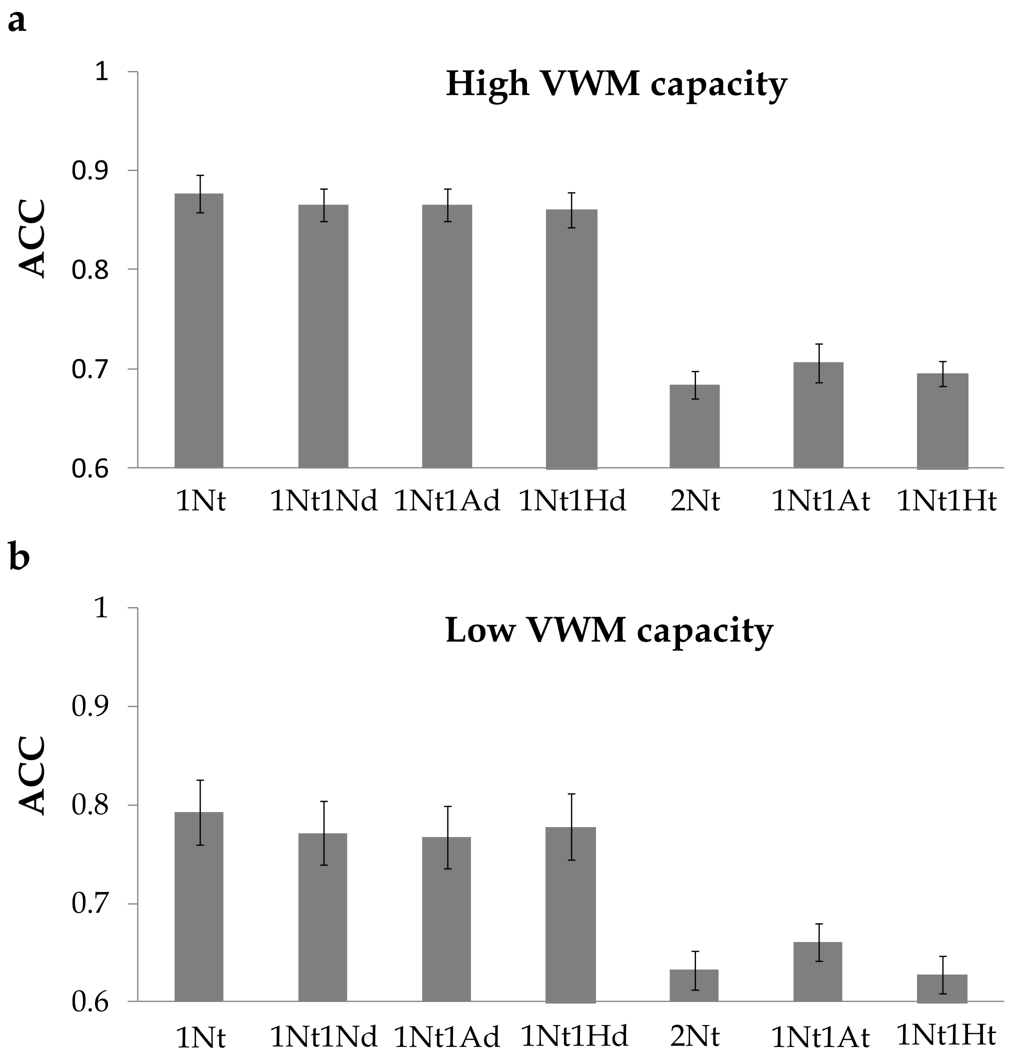

Figure 3. Accuracy in high-capacity group (a) and low-capacity group (b) separately in each condition. Mean values with error bars show standard error of mean.

Condition	High VWM capacity		Low VWM capacity	
	Accuracy	CDA amplitude	Accuracy	CDA amplitude
1Nt	0.88	-1.10	0.79	-0.93
	(0.07)	(0.98)	(0.13)	(1.18)
1Nt1Nd	0.87	-1.26	0.77	-1.40
	(0.07)	(1.04)	(0.13)	(0.88)
2Nt	0.68	-1.95	0.63	-1.44
	(0.06)	(1.11)	(0.08)	(0.82)
1Nt1Ad	0.87	-1.23	0.77	-1.45
	(0.07)	(0.88)	(0.13)	(1.34)
1Nt1At	0.71	-2.12	0.66	-1.61
	(0.08)	(1.22)	(0.08)	(1.02)
1Nt1Hd	0.86	-1.28	0.78	-0.79
	(0.07)	(1.08)	(0.13)	(1.29)
1Nt1Ht	0.70	-1.88	0.63	-1.42
	(0.05)	(1.09)	(0.08)	(1.00)

Table 1. Mean values and standard deviation (in parentheses) for behavioural accuracy and CDA amplitude in each condition.

4.2 ERP results

The CDA amplitudes in different conditions for the high- and low-capacity groups are presented in Table 1. The ANOVA showed a significant main effect of condition, $F(6,180) = 10.038$, $p < .001$, $\eta^2 = 0.251$, and a significant interaction effect of condition by group, $F(6,180) = 2.400$, $p < .05$, $\eta^2 = 0.074$, but no significant main effect of VWM capacity group, $F(1,30) = 0.604$, $p = .443$, $\eta^2 = 0.020$. Unlike the behavioural results, the CDA results showed that CDA amplitude in different conditions is modulated by the VWM capacity group. The different patterns in behavioural and ERP results may be due to the fact that CDA can index mere VWM maintenance phase.

Follow-up pairwise comparison to investigate the effects of different emotions in target faces on the VWM maintenance of facial identity was conducted. CDA amplitude was compared across the one-target, distractor and two-target conditions for each emotion (1Nt vs. 1Nt1Nd vs. 2Nt for neutral emotion; 1Nt vs. 1Nt1Ad vs. 1Nt1At for angry emotion; 1Nt vs. 1Nt1Hd vs. 1Nt1Ht for happy emotion).

4.2.1 CDA amplitude in neutral conditions

Figure 4 illustrates CDA amplitude and grand-averaged CDA waveform in neutral conditions (1Nt, 1Nt1Nd and 2Nt conditions) separately for high- and low-capacity groups.

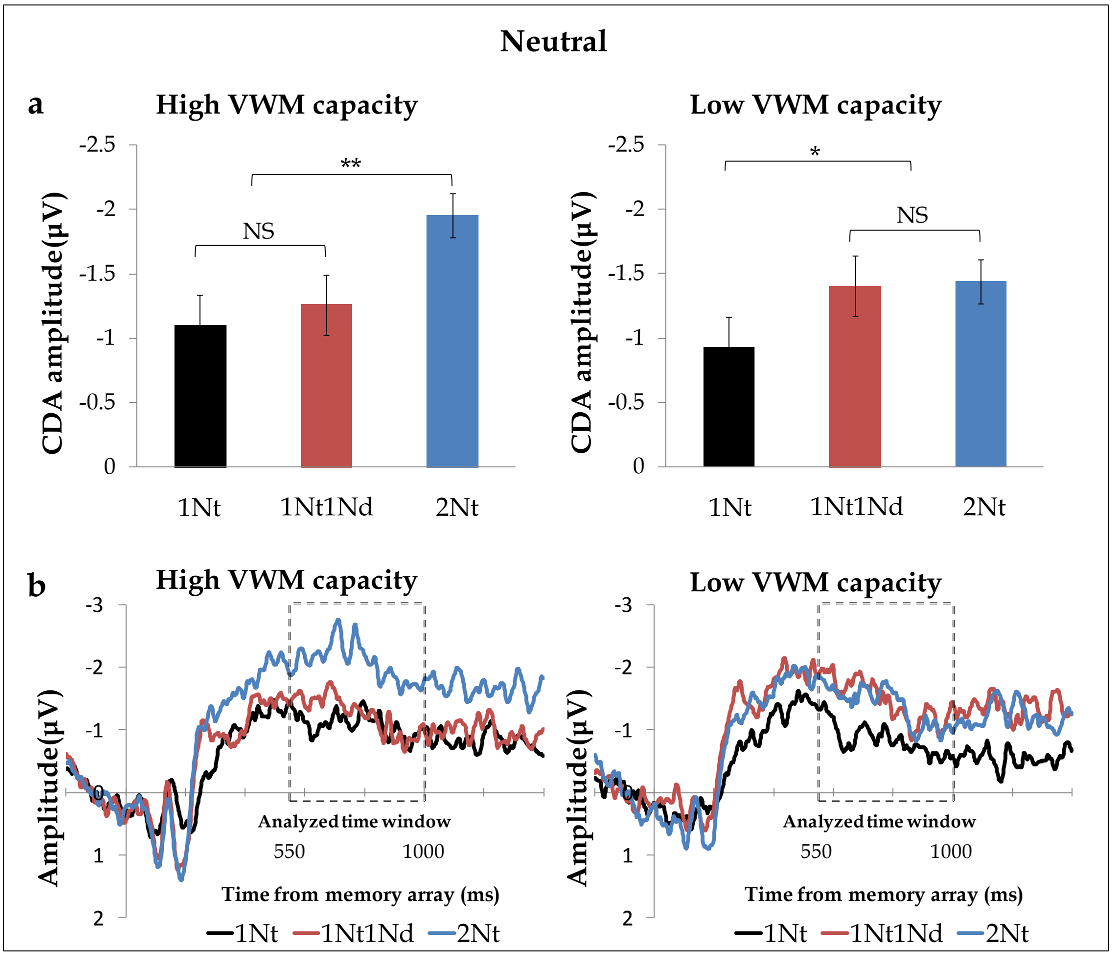

Figure 4. a) The results of the CDA amplitude for the high (left) and low (right) VWM capacity groups in neutral conditions. Mean amplitude values and their error bars show the standard error of mean. NS = non-significant; * = $p < 0.05$; ** = $p < 0.01$. b) Grand-averaged ERP waveforms time-locked to the onset of the memory array in different conditions for the high (left) and low (right) VWM capacity

groups. CDA was analysed from the area marked with the rectangle.

Results showed that in the high-capacity group, the CDA amplitude in 2Nt condition was larger than both 1Nt (t[15] = 4.006, p < .001, $CI_{95\%}$[0.48, 1.29], d = 0.81, BF_{10} = 67.98) and 1Nt1Nd (t[15] = 3.341, p < .01, $CI_{95\%}$[0.30, 1.09], d = 0.66, BF_{10} = 21.32) conditions, but there was no difference between 1Nt and 1Nt1Nd conditions (t[15] = 0.858, p = .199, $CI_{95\%}$[-0.53, 0.20], d = 0.16, BF_{10} = 0.55). In the low-capacity group, the CDA amplitudes in both 1Nt1Nd (t[15] = 2.459, p < .05, $CI_{95\%}$[-0.86, -0.11], d = 0.46, BF_{10} = 4.86) and 2Nt (t[15] = 2.521, p < .05, $CI_{95\%}$[0.10, 0.90], d = 0.51, BF_{10} = 5.36) conditions were larger than 1Nt condition, but there was no difference between 2Nt and 1Nt1Nd conditions (t[15] = 0.303, p = .384, $CI_{95\%}$[-0.20, 0.29], d = 0.04, BF_{10} = 0.33).

As expected, these results suggest that the neutral face distractors could be filtered by participants with high VWM capacity, but participants with lower VWM capacity had lower filtering efficiency. The results for filtering neutral facial distractors were consistent with previous results for filtering simple neutral distractors (Jost et al., 2011; Owens et al., 2012; Vogel et al., 2005).

4.2.2 CDA amplitude in angry conditions

Figure 5 illustrates the CDA amplitude and grand-averaged CDA waveform for the angry conditions (1Nt1Ad and 1Nt1At conditions) in comparison to 1Nt condition separately for the high- and low-capacity groups.

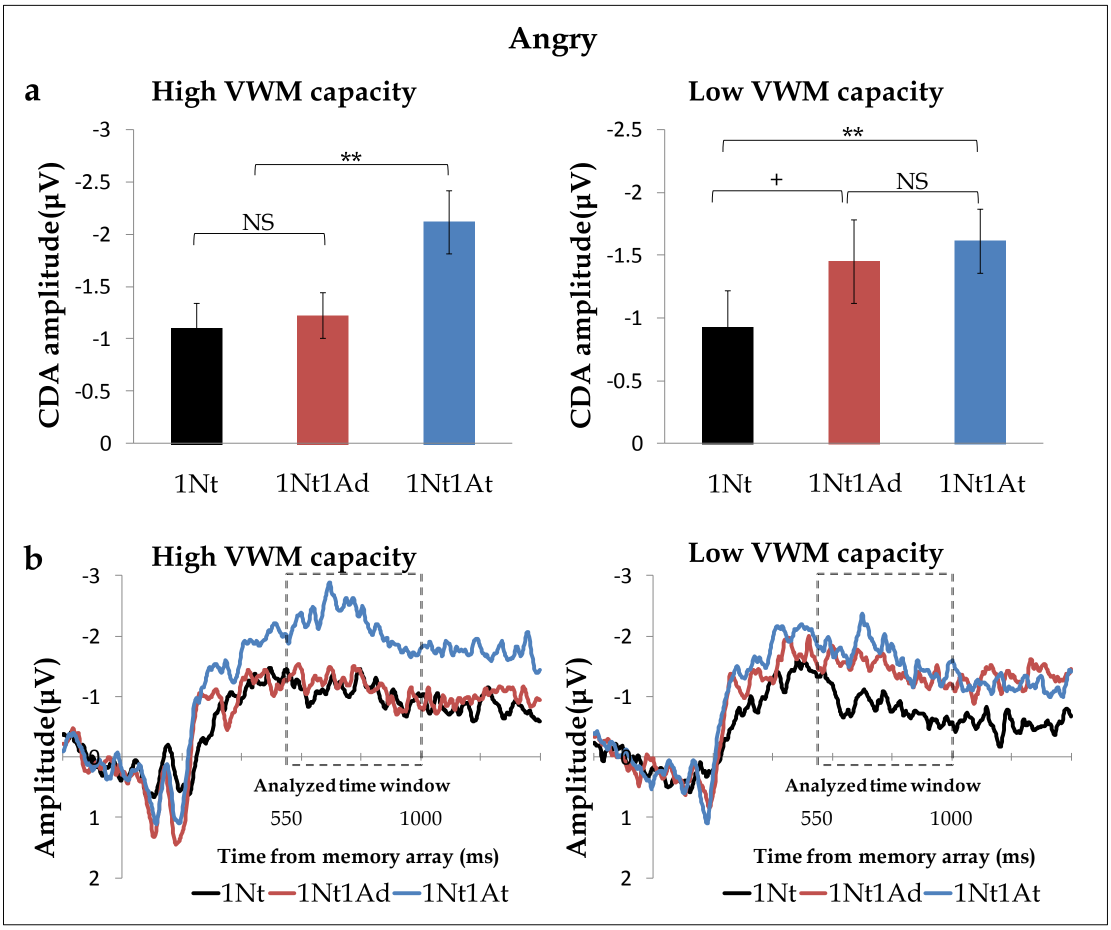

Figure 5. a) The results of the CDA amplitude for the high (left) and low (right) VWM capacity groups in the one-target condition and angry conditions. Mean amplitude values and their error bars show the standard error of mean. NS = non-significant; + = p < 0.1; ** = p < 0.01. b) Grand-averaged ERP waveforms time-locked to the onset of the memory array in different conditions for the high (left) and low (right) VWM capacity groups. CDA was analysed from the area marked with the rectangle.

The results showed that, in the high-capacity group, CDA amplitude in 1Nt1At condition was larger than in both 1Nt (t[15] = 4.069, p < .001, $CI_{95\%}$[-1.52, -0.56], d = 0.92, BF_{10} = 75.98) and 1Nt1Ad (t[15] = 4.562, p < .001, $CI_{95\%}$[0.50, 1.28], d = 0.84, BF_{10} = 179.22) conditions, but there was no difference between the 1Nt and 1Nt1Ad conditions (t[15] = 0.765, p = .228, $CI_{95\%}$[-0.44, 0.20], d = 0.13, BF_{10} = 0.50). In the low-capacity group, CDA amplitude in 1Nt1At was significantly larger than in 1Nt condition (t[15] = 3.692, p < .001, $CI_{95\%}$[-1.07, -0.35], d = 0.62, BF_{10} = 39.25), but it was not different between 1Nt1At and 1Nt1Ad conditions (t[15] = 0.600, p = .280,

$CI_{95\%}$[-0.36, 0.68], d = 0.14, BF_{10} = 0.43). CDA amplitude was marginally larger in 1Nt1Ad condition than in 1Nt condition (t[15] = 1.635, p = .063, $CI_{95\%}$[-1.16, 0.08], d = 0.42, BF_{10} = 1.42). The pattern of results for angry face conditions was similar to that of neutral face conditions. The high-capacity group efficiently filtered the angry distractors, while the low-capacity group stored angry face distractors to VWM. The result was in line with the hypothesis.

4.2.3 CDA amplitude in happy conditions

Figure 6 illustrates CDA amplitude and grand-averaged CDA waveforms for happy conditions (1Nt1Hd and 1Nt1Ht conditions) in comparison to 1Nt condition separately for the high- and low-capacity groups.

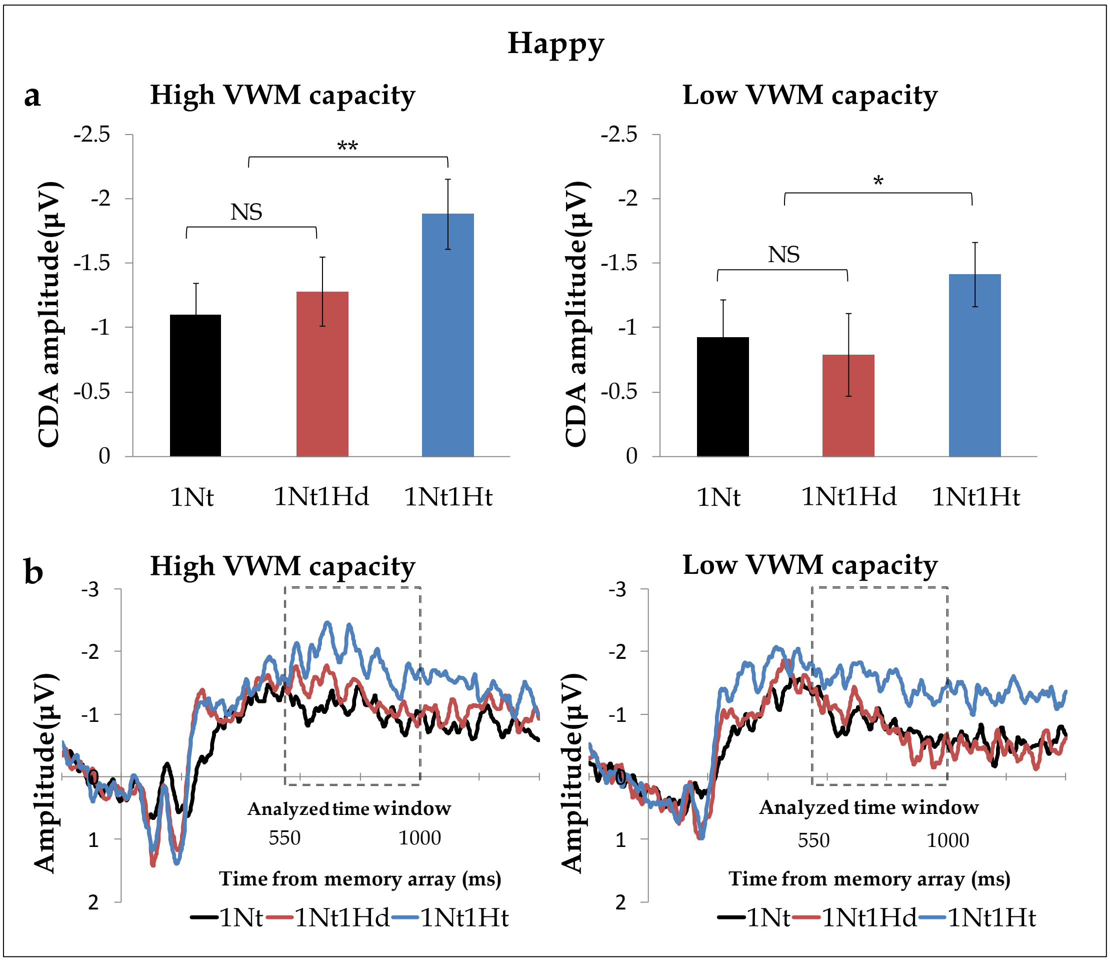

Figure 6. a) The results of the CDA amplitude for the high (left) and low (right) VWM capacity groups in the one-target condition and happy conditions. Mean amplitude values and their error bars show the

standard error of the mean. NS = non-significant; * = $p < 0.05$; ** = $p < 0.01$. b) Grand-averaged ERP waveforms time-locked to the onset of the memory array in different conditions for the high (left) and low (right) VWM capacity groups. CDA was analysed from the area marked with the rectangle.

The results showed that, in the high VWM capacity group, CDA amplitude in 1Nt1Ht condition was larger than in both 1Nt ($t[15] = 4.375$, $p < .001$, $CI_{95\%}[-1.14, -0.44]$, $d = 0.75$, $BF_{10} = 129.59$) and 1Nt1Hd ($t[15] = 5.181$, $p < .001$, $CI_{95\%}[0.38, 0.82]$, $d = 0.55$, $BF_{10} = 517.35$) conditions, but there was no difference between 1Nt and 1Nt1Hd conditions ($t[15] = 0.930$, $p = .185$, $CI_{95\%}[-0.56, 0.19]$, $d = 0.18$, $BF_{10} = 0.60$. Similar to the high-capacity group, in the low-capacity group, CDA amplitude in the 1Nt1Ht condition was significantly larger than both in 1Nt1Hd ($t[15] = 2.238$, $p < .05$, $CI_{95\%}[0.15, 1.23]$, $d = 0.54$, $BF_{10} = 3.43$) and in 1Nt ($t[15] = 1.906$, $p < .05$, $CI_{95\%}[-0.98, -0.01]$, $d = 0.45$, $BF_{10} = 2.08$) conditions, but it was not different between 1Nt and 1Nt1Hd conditions ($t[15] = 0.903$, $p = .808$, $CI_{95\%}[-0.16, 0.43]$, $d = 0.11$, $BF_{10} = 0.15$).

Interestingly, the results showed a different pattern for happy conditions compared to neutral and angry conditions. Both the high- and low-capacity groups were able to effectively filter happy face distractors. In addition, CDA amplitude increased from one target to two targets. Previous research has established that CDA amplitude reflects the number of items held in VWM, and it increases with set size and reaches an asymptotic level when the set size reaches the storage limitation (Luria et al., 2016; Vogel & Machizawa, 2004). Given the property of CDA, it can be inferred that both the high- and low-capacity groups could store one neutral face and one happy face at the same time. These results are necessary to ensure that effective filtering of happy face distractors is not due to insufficient storage space for distractors.

5. General Discussion

The main goal of the present study was to investigate the impact of VWM capacity on the filtering efficiency of emotional face distractors. It was found that the influence of VWM capacity was different for filtering different emotional faces. The individuals with high VWM capacity were able to filter all emotional faces. However, the individuals who had low VWM capacity had difficulties in filtering both angry and neutral faces but succeeded in filtering happy faces.

The results related to filtering of neutral faces mirrored the previous results of filtering simple neutral objects (Vogel et al., 2005). Both in this study, conducted with face stimuli, and in the study by Vogel et al. (2005), where non-face objects were applied, participants with high VWM capacity could filter out task-irrelevant objects, but participants with low VWM capacity maintained information about the task-irrelevant objects. This implies that the filtering mechanism for simple neutral objects (e.g. orientations or colours) could be generalised to the filtering mechanism for complex neutral objects (e.g. faces).

Quite surprisingly, the individuals with high VWM capacity were able to filter out all distractors, including the threat-related distractors (angry faces). Previous studies have shown that fearful distractors are more difficult to filter than neutral ones (Stout et al., 2013). The discrepancy between these results related to angry faces, and those related to fearful faces by Stout et al. (2013) may be due to the differences in the neural mechanisms recruited by angry and fearful faces (Fitzgerald, Angstadt, Jelsone, Nathan, & Phan, 2006; Whalen et al., 1998). Although angry faces can capture attention effectively (Fox et al., 2000; Hansen & Hansen, 1988; Pinkham et al., 2010), participants with high VWM capacity seem to have a strong ability to resist attention capture, and therefore they could filter out angry face distractors. However, as expected, the low-capacity participants had difficulties filtering angry faces. This result is in line with a previous study, which reported that participants with high VWM capacity were better at resisting attentional capture by distractor objects than those participants who had lower VWM capacity (Fukuda & Vogel, 2009).

Interestingly, participants in the low-capacity group were able to effectively filter happy face distractors. It thus seems to be that individuals with low VWM capacity have different filtering efficiencies for different emotional faces, since they were not able to filter neutral and angry distractors. One recent study may help in explaining why this is so. By using a directed forgetting paradigm, Tay and Yang (2017) found that angry faces were much more resistant to intentional forgetting than happy faces, suggesting that angry faces are better than happy faces at being retained in memory, despite participants' considerable effort to forget. Thus, it can be speculated that the low-capacity individuals may have consolidated the happy face distractors into VWM as they did for angry and neutral distractors, but they could quickly forget the happy distractors during VWM maintenance. Tay and Yang (2017) interpreted their above-mentioned results as related to attentional bias toward angry faces and cognitive resources devoted to them. This is a logical explanation in the context of these results as well. The involuntarily bias for potentially threatening expressions might have evolved because of the need to maintain more visual information to deal with potential sources of danger (e.g. potentially threatening persons). The individuals who had low VWM capacity had difficulties in filtering both angry and neutral faces. It is possible that neutral faces attracted attention as potentially threatening expressions. Happy faces, on the other hand, are more easily evaluated as non-threatening (Nummenmaa & Calvo, 2015).

There are some potential limitations in this study. As demonstrated by Stout et al. (2013), healthy participants with elevated anxiety allocated unnecessary VWM resources to fearful faces when they were irrelevant to the task at hand. Furthermore, anxiety is associated with poorer working memory capacity (Moran, 2016). Although the participants in the current study reported no current or previous psychiatric diagnoses, neither questionnaires (e.g. the State-Trait Anxiety Inventory) nor clinical interviews were used to measure anxiety. This can be seen as a potential limitation of this study. However, we have no reason to believe that the participants had elevated amount of anxiety.

Another limitation of the study is that, in order to ensure that there were equal numbers of participants in both VWM capacity groups, participants were divided into the two groups using a median split on their K_c scores, as done in several previous studies (Li et al., 2017; Owens et al., 2012; Vogel et al., 2005; Weaver et al., 2017; Zhou et al., 2011). This resulted in the VWM capacity of some participants in the two groups to be close to the median K_c, and might lead to an underestimation of the between-subject differences. In future researches on different VWM capacity groups, it would be better to first measure VWM capacity for a large sample and then choose the study sample from the two ends of the distribution to form the high- and low-capacity groups.

In summary, this study demonstrates different patterns of filtering efficiency for different emotional face distractors in individuals with high and low VWM capacity for neutral objects. Low VWM capacity seems to make the filtering of potentially threatening information (neutral and angry faces) particularly difficult. Although the results are obtained in an experimental condition, VWM capacity could influence tasks that require use of VWM to remember new people in real-life social situations.

Author Contributions Statement

QL and CY conceived and designed the experiments. QX performed the experiment. FC, CY and QX analysed the data. PA, QL and CY wrote the main manuscript text. PS, TR and QX improved the manuscript.

Conflict of interest

The authors have declared that no competing interests exist.

Data Statement

The datasets generated and analysed during the present study are available from the corresponding author on reasonable request.

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