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Social exclusion weakens storage capacity and attentional filtering ability in visual working memory

Mengsi Xu,[1,2] Lei Qiao,[1,2] Senqing Qi,[3] Zhiai Li,[4] Liuting Diao,[1,2] Lingxia Fan,[5] Lijie Zhang,[1,2] and Dong Yang[1,2]

[1]School of Psychology, Southwest University, Chongqing 400715, China, [2]Key Laboratory of Cognition and Personality (Southwest University), Ministry of Education, Chongqing 400715, China, [3]MOE Key Laboratory of Modern Teaching Technology, Shaanxi Normal University, Xi'an 710119, China, [4]The School of Psychology and Cognitive Science, East China Normal University, Shanghai 200062, China, and [5]School of Psychology, Beijing Normal University, Beijing 100875, China

Correspondence should be addressed to Dong Yang, School of Psychology, Southwest University, Tiansheng Road No. 2, BeiBei, Chongqing 400715, China. E-mail: yangd@swu.edu.cn
Mengsi Xu and Lei Qiao contributed equally to this study.

Abstract

Social exclusion has been found to impair visual working memory (WM), while the underlying neural processes are currently unclear. Using two experiments, we tested whether the poor WM performance caused by exclusion was due to reduced storage capacity, impaired attentional filtering ability or both. The Cyberball game was used to manipulate social exclusion. Seventy-four female participants performed WM tasks while event-related potentials were recorded. In Experiment 1, participants were made to remember the orientations of red rectangles while ignoring salient green rectangles. Results showed that exclusion impaired the ability to filter out irrelevant items from WM, as reflected by the similar contralateral delay activity (CDA) amplitudes for one-target-one-distractor condition and two-targets condition, as well as the similar CDA amplitudes for two-targets-two-distractors condition and four-targets condition in excluded individuals. In Experiment 2, participants were asked to remember 1–5 colored squares. Results showed that exclusion reduced storage capacity, as the CDA amplitudes reached asymptote at loads of two items for exclusion group and at loads of three items for inclusion group. Together, these two experiments provided complementary evidence that WM deficits caused by social exclusion were due to reduced storage capacity and impaired attentional filtering ability.

Key words: social exclusion; working memory; contralateral delay activity

Introduction

Humans are social beings and have a fundamental need to belong (Baumeister and Leary, 1995). However, this need to belong is often challenged by social exclusion, an aversive but prevalent phenomenon in daily life (Williams, 2007). The negative effects of being excluded are pervasive, covering mental and physical disorders (Baumeister *et al.*, 2002; Williams and Nida, 2011). Much research has explored the relationship between social exclusion and executive functions, and has reported that exclusion impairs response inhibition (Otten and Jonas, 2013), conflict monitoring (Themanson *et al.*, 2014) and interference control (Cacioppo *et al.*, 2015; Xu *et al.*, 2017). However, research about the impact of exclusion on working memory (WM), another key component of executive functions (Diamond, 2013), is still lacking. As a core component of executive function, intact WM is essential for effective cognitive

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functioning, some researchers even reported that WM could account for more than 40% of individual differences in overall performance on a broad battery of cognitive tasks (Johnson *et al.*, 2013). Therefore, the examination of how exclusion impacts WM may provide insights into the performance deficits caused by exclusion, and the present study aimed to investigate this issue.

Definitionally, WM is a limited-capacity system that involves holding information in mind and mentally working with it (Diamond, 2013). Two determined factors of WM have been proposed, the storage capacity and the attentional filtering ability (Lee *et al.*, 2010; Li *et al.*, 2017). The storage capacity is the basic feature of WM and supports processing of information in WM. A larger storage capacity provides greater chance for better WM performance (Johnson *et al.*, 2013). As for the attentional filtering ability, given that people can hold only about four units of information in WM, it is important to filter out irrelevant items and to ensure that WM is filled with only relevant information (Vogel *et al.*, 2005). Some studies have investigated the relationship between these two factors and have indicated that they are strongly related (Gaspar *et al.*, 2016; Li *et al.*, 2017). On the one hand, storage capacity and the attentional filtering ability have been found to be positively correlated (Vogel *et al.*, 2005; Gaspar *et al.*, 2016). On the other hand, they are still different in many aspects, such as in definition (i.e. storage capacity is more basic cognitive control, while attentional filtering is relative higher-order cognitive control), and in physiological foundation (i.e. storage capacity is primarily related to parietal cortex, and attentional filtering is mainly related to prefrontal cortex and basal ganglia, Lee *et al.*, 2010; Jahfari *et al.*, 2011; Buelow *et al.*, 2015; Li *et al.*, 2017).

Currently, several studies have explored the potential effect of exclusion on WM and reported that exclusion impairs WM, but the nature of this impairment is ambiguous (Hawes *et al.*, 2012; O'Luanaigh *et al.*, 2012; Fisher, 2014; Buelow *et al.*, 2015). To illustrate, in the Fisher (2014) study, a Reading-Span task was used to assess WM. Excluded participants were presented with a series of sentences (they were asked to count the number of vowels) that alternated with individual words, and were asked to recall the words at the end of the series. Results showed that excluded participants exhibited worse performance relative to included ones, indicating that exclusion hindered WM. Similarly, O'Luanaigh *et al.* (2012) asked excluded participants to perform a Letter-Number Sequencing task (Wechsler, 2014) and replicated the hindrance effect of exclusion on WM. Remarkably, an important methodological problem exists in these studies, that is, the complex span tasks which are used here to asses WM have dual-task characteristics as they require the person to simultaneously retain information (e.g. words) while carrying out processing (e.g. couting vowels, Cowan *et al.*, 2005). Thus, it is not clear whether the poor performance on such tasks caused by exclusion is due to reduced storage capacity, inability to filter out irrelevant information or both (Vogel *et al.*, 2005; Lee *et al.*, 2010).

Consequently, in the present study, we aimed to explore the above-mentioned question and clarify the nature of WM deficits caused by social exclusion. In other words, whether the poor WM performance caused by exclusion was due to a reduced storage capacity, attentional filtering deficits or both (Lee *et al.*, 2010). Although there were no direct studies exploring this issue, many indirect sudies could provide some useful clues (Otten and Jonas, 2013; Qi *et al.*, 2014a; Qi *et al.*, 2014b; Gaspar *et al.*, 2016). To be specific, as many studies have demonstrated that self-regulation of exclusion-related negative feelings would deplete limited attentional resources, and leave insufficient resources for following cognitive control (Baumeister *et al.*, 2002; Chester and DeWall, 2014), it might be reasonable to expect that social exclusion impairs both storage capacity and attentional filtering ability. Besides, this impairment expectation was also supported by the inference from other perspectives: first, many evidences have shown that exclusion impairs response inhibition (Otten and Jonas, 2013; Xu *et al.*, 2016), thus it was logical to expect parallel impairment effect of exclusion on another inhibitory control, namely the attentional filtering ability (Diamond, 2013); then, as storage capacity was positively correlated with inhibition ability (Gaspar *et al.*, 2016), it might be probable that exclusion would exert similar hindrance impact on storage capacity. More importantly, as social exclusion is closely related with anxiety (Leary, 1990), recent studies which examined the modulation effect of anxiety on WM (storage capacity and attentional filtering ability) and found that anxiety impaired both storage capacity and attentional filtering ability (Qi *et al.*, 2014a; Qi *et al.*, 2014b), could provide us inspiring clues. Together, these evidences seem to support the hypothesis that social exclusion weakens the storage capacity as well as the attentional filtering ability.

To verify this hypothesis, a lateralized change detection task similar to Vogel *et al.* (2005) was used, in which participants were cued to remember the orientations of red rectangles on the cued side of a computer display while ignoring green distractors. The initial display consisted of either one-red-one-green (i.e. 1 target and 1 distractor, 1T1D for short), two-red (2T), two-red-two-green (2T2D) or four-red (4T) rectangles on each side of the screen. After a short retention interval, the array was presented again (Figure 1). Participants then judged whether the orientation of any of the red rectangles on the attended side had changed slightly.

In consideration that behavioral outcomes only provide indirect measurements of underlying cognitive processing (Qi *et al.*, 2014a; Cohen, 2017), we recorded event-related potentials (ERPs) during the lateralized change detection task, and mainly focused on the more direct electrophysiological measurements, the contralateral delay activity (CDA), which is a sustained negative voltage at posterior electrodes during the representation of items in WM (Vogel *et al.*, 2005). Previous studies with lateralized change detection paradigm have demonstrated the successfulness of using CDA to examine the storage capacity and the filtering ability (Vogel and Machizawa, 2004; Vogel *et al.*, 2005; Luria *et al.*, 2016). Specifically, Vogel and Machizawa (2004) asked participants to perform a lateralized change detection task, in which participants were required to remember 1–10 colored squares on the cued side of a display. They found that the CDA amplitude could be used to reflect the amount of information held in WM, as its amplitude increased with increasing representations of items and reached an asymptote at the WM capacity of an individual. In another study, Vogel *et al.* (2005) added distractors into the lateralized change detection task, and asked participants to remember the orientations of red rectangles, sometimes in the presence of task-irrelevant distractors (blue rectangles). They found that for people with low WM capacity, the CDA amplitudes for remembering two red items along with two blue distractors were equivalent to those for remembering four red items alone, indicating that these people were inefficient at excluding the irrelevant items from memory. While for people with high WM capacity, the CDA amplitudes for remembering two red items along with distractors were equivalent to those for remembering two red items only,

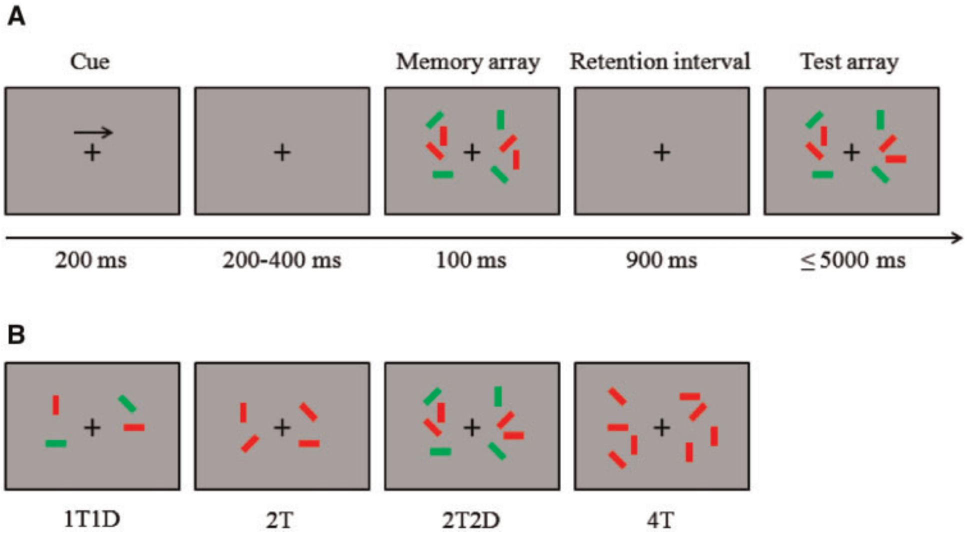

Fig. 1. Stimulus sequence and experimental conditions in Experiment 1. (A) Example of a 2T2D condition in which the right hemifield was task relevant. (B) Four task conditions in Experiment 1. 1T1D, one-target-one distractor; 2T, two-targets; 2T2D, two-targets-two-distractors and 4T, four-targets.

indicating that these people were efficient at representing only the red items and excluding the irrelevant items from memory.

Therefore, following previous studies (Vogel *et al.*, 2005; Lee *et al.*, 2010), to examine exclusion's effect on storage capacity, the CDA amplitudes for 1T1D, 2T, 2T2D and 4T conditions were compared between groups. Smaller CDA amplitudes should be observed for excluded than for included participants if exclusion did impair the storage capacity. To examine exclusion's effect on the attentional filtering ability, the CDA amplitudes for 1T1D and 2T2D conditions were compared to those for 2T and 4T conditions for both excluded and included participants. Two comparisons were conducted. Firstly, to test the harder or higher-level filtering ability (filter out two distractors here in 2T2D condition), the critical question was whether the CDA amplitudes for 2T2D condition would be more similar to 2T or 4T condition. If excluded participants could successfully filter out distractors, then they needed to retain only two items in memory, thus similar CDA amplitudes should be observed between 2T2D and 2T conditions as well. If excluded participants could not ignore distractors, then they had to retain four items, resulting in similar CDA amplitudes between 2T2D and 4T conditions. Secondly, to test the easier or lower-level filtering ability (filter out one distractor here in 1T1D condition), the CDA amplitudes for 1T1D condition were compared to those for 2T condition, similar CDA amplitudes should be observed for 1T1D and 2T conditions among excluded participants, if exclusion impairs basic filtering ability.

Experiment 1

Methods

Participants. Thirty-eight female volunteers (18–22 years; M = 19.41 years, s.d. = 0.94) took part in this experiment and were randomly assigned to either the inclusion or exclusion group. Six participants (three for each group) were excluded due to excessive rates of ocular artifacts, resulting in sixteen participants for each group. We chose only female participants as previous research has shown that females are more likely to suffer from exclusion (Benenson *et al.*, 2013). This research protocol was approved by the Local Ethics Committee.

Materials and procedure

Cyberball game. Cyberball game was used to manipulate social exclusion (Williams, 2007), in which participants played a virtual toss game with two other players (one male and one female) that they did not know and did not expect to meet. We manipulated the degree of social exclusion and inclusion by varying the number of times participants received the ball from the other players. Participants in the inclusion group received the ball in approximately one-third of the total throws (42 total throws), while participants in the exclusion condition only received the ball twice at the beginning of the game.

Need threat scale. After finishing the Cyberball game, participants completed the 20-item Need Threat Scale (van Beest and Williams, 2006). This scale asked participants to self-assess their level of satisfaction for feelings of belonging, self-esteem, meaningful existence and control during the game on a seven-point scale (1 = 'do not agree' to 7 = 'agree'; Cronbach's $\alpha = 0.92$, van Beest and Williams, 2006). Lower scores represent an increased perceived threat to social needs and indicated the effectiveness of the social exclusion manipulation.

Positive and negative affect schedule. Participants also completed the 20-item Positive and Negative Affect Schedule (PANAS, Watson *et al.*, 1988). The PANAS includes 10 items assessing positive emotions (e.g. interested) and 10 items assessing negative emotions (e.g. irritable). Participants were instructed to self-assess their current emotional state on a five-point scale (1 = 'very slightly or not at all' to 5 = 'extremely'; Cronbach's $\alpha = 0.82$, Huang *et al.*, 2003).

Lateralized change detection task. In an electromagnetically shielded room, participants were seated comfortably about 80 cm from a 19 inches screen. They performed a lateralized change detection task adapted from Vogel *et al.* (2005), in which they were cued to remember the information on one side of the display and ignore the information on the other side. To isolate the CDA from other task general brain activity, the CDA was measured as the difference in mean amplitudes between activity in the hemispheres contralateral and ipsilateral to the to-be-remembered information (Arend and Zimmer, 2011). Thus, bilateral displays are crucial for isolating the CDA. In each trial (Figure 1A), the participants were presented with a brief bilateral array of colored rectangles (each 0.41° × 1.42°) of varying orientations (vertical, horizontal, left 45° and right 45°). The two stimulus arrays were presented within 4° × 7.6° rectangular regions that were presented 2.8° to the left and right of a central fixation cross on a gray background. The stimulus positions were randomized, with the constraint that the distance between rectangles within a hemifield was at least 2°. The numbers of targets and distractors were always the same in both hemifields; only the location and color of the stimuli could differ between hemifields. The task was to remember the orientations only of the red items (RGB: 200, 0, 0) and to ignore the green ones (RGB: 25, 255, 52) in either the left or the right hemifield. The RGB values of the colors were converted to Lch values (red, Lch = 42/87/40; green, Lch = 88/113/138, http://colormine.org/convert/rgb-to-lch). Green distractors were more physically salient relative to the red items, as the luminance of green was higher than that of red.

Each trial began with a 200 ms arrow presented above a fixation cross. The arrow cued participants to remember the orientations of only the red items in either the left or the right side of the memory array. Following a variable interval of 200 to 400 ms, a memory array was presented for 100 ms. The memory array was removed from the display for 900 ms (delay/retention period). The test array was then displayed for a maximum of 5000 ms. Participants responded by pressing one of two vertically aligned keys to indicate whether or not a change was present. In one-half of the trials, the memory and test arrays were identical, whereas in the other half, the orientation of a single red rectangle within the to-be-remembered side of the memory array was different from its orientation in the test array. Key allocations were counter-balanced between the participants. The instructions emphasized accuracy rather than speed. Moreover, participants were also instructed to keep their eyes fixated throughout the task. The intertrial interval was 2000 ms.

The four conditions differed in their numbers of targets (red rectangles) and distractors (green rectangles) (Figure 1B). In the one-target-one-distractor condition (1T1D), one red item along with one green distractor was shown on each side of the display. In the two-targets condition (2T), only two red items were shown on each side of the display. In the two-targets-two-distractors condition (2T2D), two red items along with two green distractors were shown on each side of the display. In the four-targets condition (4T), only four red items were shown on each side of the display. These four conditions were presented in random order in each block. Ten blocks were presented, and each block included sixty trials. Overall, participants experienced 150 trials for each type of memory array (i.e. 1T1D, 2T, 2T2D, 4T). At the beginning of the session, the participants completed a practice block of 24 trials (six per condition). They were given a short break after each block.

EEG recording and processing. Electrical brain activity was recorded at 64 scalp sites, using tin electrodes mounted in an elastic cap (Brain Product, Munich, Germany), with references at the left and right mastoids and a ground electrode at the medial frontal aspect. Vertical electrooculograms (EOGs) for the right eye were recorded supra- and infra-orbitally. Horizontal EOG was recorded as the left *vs* right orbital rim. All electrode impedance was < 5 kΩ. EEGs and EOGs were amplified using a 0.05–100 Hz bandpass and continuously digitized at 500 Hz/channel. Offline, the data were referenced to the average for the left and right mastoids (average mastoid reference), and a bandpass filter of 0.1–30 Hz was applied. Trials containing saccades (horizontal EOG exceeding ± 25 μV), blinks (Fpz exceeding ± 60 μV, vertical EOG exceeding ± 80 μV) or muscle artifacts (all other electrodes exceeding ± 80 μV) were removed from further analyses (Qi *et al.*, 2014a). The percentages of trials excluded from the averaging due to artifacts were 36.50% for exclusion group and 34.15% for inclusion group. Only trials with correct responses were analyzed.

Measures and analyses

Behavioral analyses

First, in order to the test whether the exclusion manipulation was effective, the Need Threat Scale and PANAS scores were separately analyzed with an independent sample *t*-test between exclusion and inclusion groups. Then, for the lateralized change detection task, our primary measure was *K*-score, an estimate of the number of items held in and then retrieved from WM (Cowan, 2001). Pashler's formula was used because our task used whole-display probes (Rouder *et al.*, 2011). Specifically, $K = N \times (HR - FA)/(1 - FA)$, where *K* is WM capacity; *N* is the number of to-be-remembered items; HR is the hit rate or the proportion of correct responses when a change is present and FA is the false alarm rate or the proportion of incorrect responses on no-change trials. *K*-score was entered into a 2 × 4 mixed analysis of variance (ANOVA), with group (exclusion, inclusion) as the between-subjects factor and memory load (1T1D, 2 T, 2T2D, 4 T) as the within-subjects factor.

ERP analyses

The averaged epoch for the ERPs was 1400 ms, including 200 ms pre-memory-array and 1200 ms post-memory-array onset. Separate averages were computed for each participant in each of the memory loads (1T1D, 2T, 2T2D, 4T), and for contralaterality (electrode contralateral *vs* ipsilateral to the location of memory items). Contralateral waveforms were calculated as the average of the left-sided electrodes to the right-sided items and of the right-sided electrodes to the left-sided items. Ipsilateral waveforms were calculated as the average of the left-sided electrodes to the left-sided items and of the right-sided electrodes to the right-sided items. The CDA was then computed as the difference in mean amplitudes between the activity in hemispheres contralateral and ipsilateral to the memory items during the retention period. On the basis of previous research (Vogel and Machizawa, 2004; Qi *et al.*, 2014a), mean activity from five pairs of lateral posterior electrode sites (P3/4, P5/6, P7/8, PO3/4 and PO7/8) within the time period of 300–900 ms after onset of the memory array was used to calculate the CDA component. The resulting amplitudes of CDA were entered into a 2 × 4 mixed ANOVA, with group (exclusion, inclusion) as the between-subjects factor and memory load (1T1D, 2T, 2T2D, 4T) as the within-subjects factor. To be specific, to examine exclusion's effect on storage capacity, the CDA amplitudes for 1T1D, 2T, 2T2D and 4T conditions were separately compared between groups. To examine exclusion's effect on the attentional filtering ability, the CDA amplitudes for 1T1D and 2T2D conditions were compared to those for 2T and 4T conditions for both excluded and included participants.

Moreover, as CDA amplitude is influenced by many factors (e.g. location and orientation of the dipole, skull thickness, placement of the electrode cap etc.), differences in absolute amplitude between the exclusion and inclusion groups might be due to these ancillary factors. Therefore, following previous studies (Vogel and Machizawa, 2004; Vogel *et al.*, 2005), we made additional analyses by computing the difference in CDA amplitude between comparable conditions to index storage capacity (i.e. 2T–4T) and filtering ability (i.e. 2T2D–2T), respectively. These two indexes were then separately analyzed with independent-samples *t*-tests between exclusion and inclusion groups. The larger index of storage capacity represents stronger representation capacity, and a larger index of filtering ability represents stronger filtering ability (since larger 2T2D–2T difference score might indicate less unnecessary storage of distractor, namely, stronger filtering ability). For all analyses, Greenhouse-Geisser adjustments to the degrees of freedom were used where appropriate.

Results

Behavioral data

Manipulation checks. For the Need Threat scores, the results revealed lower scores for the exclusion ($M = 3.28$, s.d. $= 0.98$) than for the inclusion group ($M = 4.79$, s.d. $= 1.07$), $t\ (30) = -4.16$, $P < 0.001$, power $(1\text{–}\beta) = 0.98$ (Faul *et al.*, 2007). These results suggest that the needs of excluded participants were threatened compared to those of the included participants, confirming the effectiveness of the exclusion manipulation.

For the PANAS scores, the results demonstrated that neither positive nor negative emotion scores differed significantly between the exclusion and inclusion groups [positive: exclusion group ($M = 26.38$, s.d. $= 6.08$) *vs* inclusion group ($M = 29.63$, s.d. $= 4.92$), $t\ (30) = -1.66$, $P = 0.107$, power $(1\text{–}\beta) = 0.36$; negative: exclusion group ($M = 19.06$, s.d. $= 5.28$) *vs* inclusion group ($M = 16.75$, s.d. $= 6.21$), $t\ (30) = 1.13$, $P = 0.266$, power $(1\text{–}\beta) = 0.85$]. Consistent with previous studies, these results suggest that excluded participants did not show explicit emotional responses (Twenge *et al.*, 2003).

Lateralized change detection task. A repeated measures ANOVA showed a significant main effect of group, $F\ (1,\ 30) = 6.09$, $P = 0.020$, $\eta^2_p = 0.17$, power $(1\text{–}\beta) = 0.82$, with larger K scores for inclusion group ($M = 1.83$, s.d. $= 0.17$) than for exclusion group ($M = 1.68$, s.d. $= 0.17$); and a significant main effect of memory load, $F\ (3,\ 90) = 413.60$, $P < 0.001$, $\eta^2_p = 0.93$, power $(1\text{–}\beta) = 1.00$. The interaction between group and memory load was also significant, $F\ (3,\ 90) = 3.05$, $P = 0.033$, $\eta^2_p = 0.09$, power $(1\text{–}\beta) = 1.00$. Further analyses showed that K scores for exclusion group were smaller than that for inclusion group at 2T, 2T2D and 4T conditions ($P = 0.037$, $P = 0.021$, $P = 0.044$, respectively), but only showed a trend to be significant in 1T1D condition ($P = 0.100$).

ERP data. Figure 2 shows grand-average ERP difference waves (contralateral-minus-ipsilateral) for both the exclusion and inclusion groups at each memory load. A repeated measures ANOVA yielded a significant main effect of memory load, $F\ (3,\ 90) = 11.38$, $P < 0.001$, $\eta^2_p = 0.28$, power $(1\text{–}\beta) = 1.00$. Moreover, the interaction effect between memory load and group was also significant, $F\ (3,\ 90) = 3.2$, $P = 0.027$, $\eta^2_p = 0.10$, power $(1\text{–}\beta) = 1.00$. Further analyses showed that in the inclusion group, the CDA amplitude of the 1T1D condition was significantly smaller than that of the 2T condition ($P = 0.003$), and the 2T2D condition was significantly smaller than the 4T condition ($P = 0.040$), but no significant difference was observed between the 2T condition and the 2T2D condition ($P = 0.767$). This result indicated that included individuals could efficiently exclude the distractors. In contrast, in the exclusion group, no significant differences on CDA amplitude were observed between the 1T1D condition and the 2T condition ($P = 0.438$), and between the 2T2D condition and the 4T condition ($P = 0.411$), but the 2T condition was significantly smaller than the 2T2D condition ($P = 0.012$). This result indicated that excluded individuals were highly inefficient at keeping the irrelevant items out of memory. No significant group differences were observed on CDA amplitudes of 1T1D, 2T, 2T2D and 4T conditions (all $Ps > 0.159$).

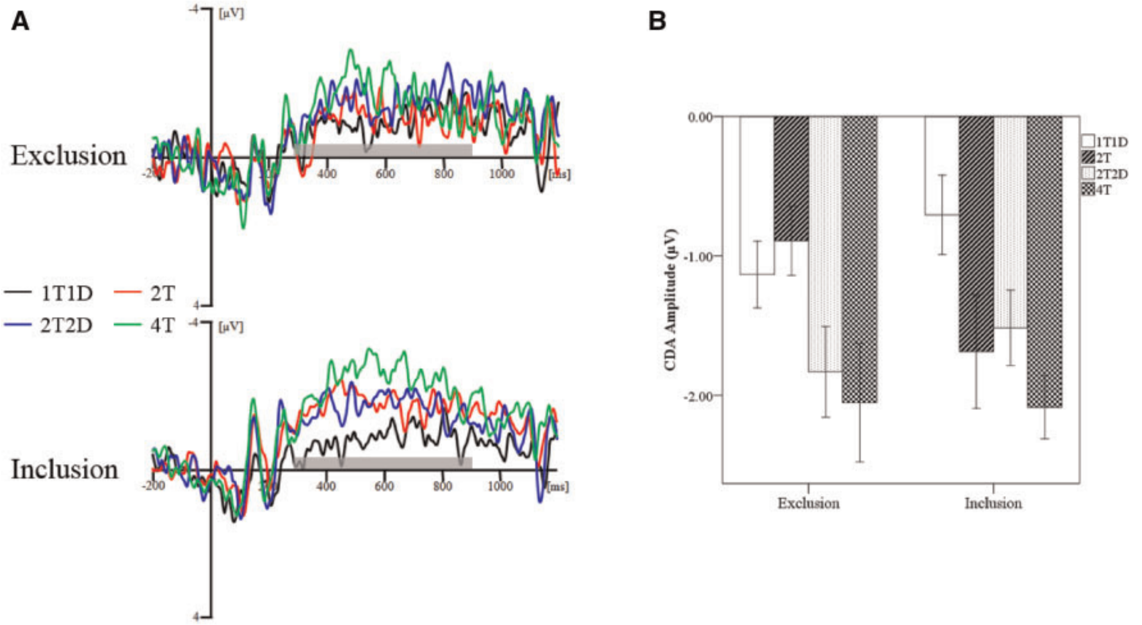

Fig. 2. ERP results in Experiment 1. (A) Grand-average ERP waveforms time-locked to memory array onset showing the CDA difference waves for each group at each memory load. (B) Mean amplitude of CDA between 300 and 900 ms after memory array onset. Error bars represent standard errors of the means (SEMs).

Moreover, the *t*-test on index of storage capacity (2T–4T) revealed no significant result (exclusion group: $M = 1.16$, s.d. = 1.44 *vs* inclusion group: $M = 0.47$, s.d. = 1.47), $t\ (30) = 1.350$, $P = 0.187$, power $(1–\beta) = 0.25$; but the *t*-test on index of filtering ability (2T2D–2T) revealed significant result (exclusion group: $M = -0.94$, s.d. = 0.82 *vs* inclusion group: $M = 0.10$, s.d. = 1.81), $t\ (30) = -2.10$, $P = 0.044$, power $(1–\beta) = 0.53$, with smaller index of filtering ability for exclusion than for inclusion group, indicating that excluded individuals were inefficient at keeping the irrelevant items out of memory relative to included individuals.

Discussion. The aim of Experiment 1 was to determine whether the poor performance caused by exclusion was due to reduced storage capacity, deficit in attentional filtering or both. Consistent with our hypotheses, we found that exclusion did impair attentional filtering ability, as evidenced by the similar CDA amplitudes between 1T1D and 2T conditions and the similar CDA amplitudes for 2T2D and 4T conditions in exclusion group. Furthermore, these results still showed similar pattern after excluding factors which might influence the raw CDA amplitudes by using the difference in CDA amplitude between 2T2D and 2T conditions to index filtering ability, as evidenced by smaller index of filtering ability for exclusion than for inclusion group. These impairment effects of exclusion on filtering ability are in line with previous studies that observed exclusion impaired response inhibition (Lurquin *et al.*, 2014; Xu *et al.*, 2016), but also extend previous studies to demonstrate the generality of inhibition control failure in excluded individuals (both response inhibition and filtering ability). Moreover, these impairments were more general, not only in condition where harder or higher-level filtering ability was needed (2T2D condition, where two distractors were needed to be filtered out), but also in condition where easier or lower-level filtering ability was needed (1T1D condition, where one distractor was needed to be filtered out).

Nevertheless, we failed to obtain evidence to support the notion that exclusion reduces storage capacity, as no group differences in CDA amplitudes were observed (on 1T1D, 2T, 2T2D and 4T conditions), neither group difference in storage capacity index (2T–4T) was found. Before drawing a conclusion that exclusion exerts no impairment effect on storage capacity, several important issues should be noted. First, the memory load in our study was only at low to moderate level (2 or 4 items), while some researchers have showed that exclusion reduced storage capacity only when the load was high (Buelow *et al.*, 2015). Second, the memory materials used in our study contained two feature attributes (i.e. colors and orientations), while previous studies usually measured storage capacity with memory materials containing single feature attribute (e.g. colors, Vogel and Machizawa, 2004; Qi *et al.*, 2014a). Importantly, some researchers have showed that the CDA was modulated by the complexity of feature attributes (e.g. both four orientation items and four color-orientation conjunction items elicited larger CDA than four color items, Woodman and Vogel, 2008; Luria *et al.*, 2010). Third, although we mainly focused on the ERP results, as the behavioral results were indirect measurements and often led to inaccurate conclusions (Otten and Jonas, 2013; Xu *et al.*, 2016), the significantly larger *K* scores for inclusion group than for exclusion group in present study should arouse our attention. Based on these considerations, we thought it was necessary to carefully reexamine exclusion's effect on storage capacity. Therefore, in Experiment 2, we reexamined whether exclusion exerted an influence on storage capacity with another lateralized change detection task, which has been successfully used to explore WM capacity (Vogel and Machizawa, 2004; Qi *et al.*, 2014a). In other words, the Experiment 2 was generally the same as Experiment 1, but with colored squares as targets and without distractors. Participants were required to remember 1–5 colored squares of the items on one side of the memory array across a short retention period, and then indicate whether or not one of the to-be-remembered items changed color in the test array.

Experiment 2

Methods

Participants. Another thirty-six female volunteers (18–22 years; $M = 19.75$ years, s.d. = 1.13) took part in this experiment and were randomly assigned to either the inclusion or exclusion group. Two participants (one for each group) were excluded due to excessive rates of ocular artifacts, resulting in seventeen participants for each group.

Materials and procedure. Cyberball game, Need Threat Scale and PANAS were used similarly as Experiment 1.

Lateralized change detection task. All procedures in Experiment 2 were the same as Experiment 1, except for the following changes (Figure 3). First, participants were required to remember 1–5 colored squares ($0.68^\circ \times 0.68^\circ$, RGB values, red: 255, 0, 0; green: 0, 255, 0; blue: 0, 0, 255; yellow: 255, 255, 0; purple: 160, 32, 240; black: 0, 0, 0 and white: 255, 255, 255) on one side of the memory array across a short retention period, and then indicate whether or not one of the to-be-remembered items changed color in the test array. Second, 12 blocks were presented, and each block included 80 trials. Overall, there were 192 trials for each memory load (i.e. 1, 2, 3, 4 or 5 to-be-remembered items on each side). At the beginning of the session, the participants completed a practice block of 20 trials (four per memory load).

EEG recording and processing. All manipulations in Experiment 2 were the same as Experiment 1. The percentages of trials excluded from the averaging due to artifacts were 17.72% for exclusion group and 15.25% for inclusion group.

Measures and analyses. All analyses in Experiment 2 were the same as Experiment 1, except that the *K*-score and CDA amplitudes were separately entered into a 2×5 mixed ANOVA, with group (exclusion, inclusion) as the between-subjects factor and memory load (1–5) as the within-subjects factor. Moreover, similar to Experiment 1, we made additional analyses by computing the difference in CDA amplitude between comparable conditions to index storage capacity. Specifically, the 2T–4T difference was used as an index to represent storage capacity at load 4, and the 2T–5T difference was used as an index to represent storage capacity at load 5. These two indexes were then separately analyzed with independent-samples *t*-tests between exclusion and inclusion groups, with larger index represents stronger representation capacity.

Results

Behavioral data

Manipulation checks. For the Need Threat scores, the results revealed lower scores for the exclusion ($M = 3.38$, s.d. = 0.88) than for the inclusion group ($M = 5.03$, s.d. = 0.89), $t\ (32) = -5.43$,

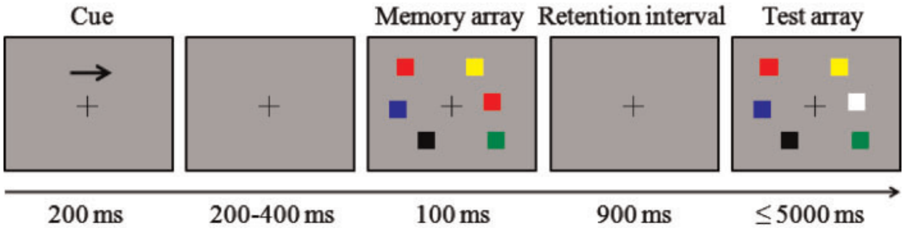

Fig. 3. Trial structure of the change detection task in Experiment 2. A change trial with memory load 3 in which the colors of right items are to be remembered (as indicated by the arrow cue).

$P < 0.001$, power $(1–\beta) = 1.00$. These results suggest that the needs of excluded participants were threatened compared to those of the included participants, confirming the effectiveness of the exclusion manipulation.

For the PANAS scores, the results demonstrate that neither positive nor negative emotion scores differed significantly between the exclusion and inclusion groups [positive: exclusion group ($M = 26.88$, s.d. $= 7.01$) *vs* inclusion group ($M = 28.82$, s.d. $= 5.55$), t (32) $= -0.67$, $P = 0.377$, power $(1–\beta) = 0.14$; negative: exclusion group ($M = 20.47$, s.d. $= 8.60$) *vs* inclusion group ($M = 17.71$, s.d. $= 9.01$), t (32) $= 0.92$, $P = 0.367$, power $(1–\beta) = 0.98$].

Lateralized change detection task. A repeated measures ANOVA showed no significant main effect of group or interaction between group and memory load for K scores, F (1, 32) $= 2.78$, $P = 0.105$, $\eta^2_p = 0.08$, power $(1–\beta) = 0.49$ and F (4, 128) $= 1.62$, $P = 0.213$, $\eta^2_p = 0.05$, power $(1–\beta) = 0.42$. However, a significant main effect of memory load was observed, F (4, 128) $= 142.73$, $P < 0.001$, $\eta^2_p = 0.82$, power $(1–\beta) = 1.00$, indicating that there was an increase in K scores as more items were required to be encoded. Post hoc tests showed that K scores significantly increased from load 1 to load 4 (all $P < 0.006$); and K scores of load 4 did not differ from those of load 5 ($P = 1.000$). The data showed that in both groups K scores reached maximum values at load 4.

ERP data. Figure 4 shows grand-average ERP difference waves (contralateral-minus-ipsilateral) for both the exclusion and inclusion groups at each memory load. A repeated measures ANOVA yielded a significant main effect of memory load, F (4, 128) $= 20.13$, $P < 0.001$, $\eta^2_p = 0.39$, power $(1–\beta) = 1.00$. Moreover, the interaction effect between memory load and group was also significant, F (4, 128) $= 2.70$, $P = 0.034$, $\eta^2_p = 0.08$, power $(1–\beta) = 1.00$. To examine the asymptote of the CDA in each group, subsequent post hoc tests were conducted within each group. For the exclusion group, the CDA amplitudes significantly increased from load 1 to load 2 ($P = 0.016$); but stopped increasing from load 2 to load 3 ($P = 0.114$). For the inclusion group, the CDA amplitudes significantly increased from load 1 to load 2 ($P = 0.001$), and from load 2 to load 3 ($P = 0.002$), but the CDA amplitude of load 3 did not differ from that of load 4 ($P = 0.217$). The data indicated that the CDA amplitudes reached asymptote at load 2 for the exclusion group and at load 3 for the inclusion group.

In addition, to examine group differences in CDA amplitudes at each memory load, independent samples t-tests (two-tailed) were conducted between the exclusion and inclusion groups. The results showed a more negative CDA for the inclusion group than for the exclusion group at memory load 5 [t (32) $= -2.45$, $P = 0.020$], but not at load 1 [t (32) $= -0.07$, $P = 0.946$], load 2 [t (32) $= -0.73$, $P = 0.468$], load 3 [t (32) $= -1.46$, $P = 0.154$] and load 4 [t (32) $= -0.75$, $P = 0.459$]. The data therefore showed that group differences in CDA amplitudes only emerged at higher load levels.

Moreover, the t-test on index of storage capacity at load 4 (i.e. 2T–4T) revealed no significant result (exclusion group: $M = 0.24$, s.d. $= 0.55$ *vs* inclusion group: $M = 0.23$, s.d. $= 0.62$), t (32) $= 0.07$, $P = 0.943$, power $(1–\beta) = 0.05$; but the t-test on index of storage capacity at load 5 (i.e. 2T–5T) revealed significant result (exclusion group: $M = 0.09$, s.d. $= 0.57$ *vs* inclusion group: $M = 0.57$, s.d. $= 0.34$), t (32) $= -2.99$, $P = 0.005$, power $(1–\beta) = 0.82$, with smaller index for exclusion than for inclusion group, indicating that excluded individuals showed reduced representation capacity relative to included individuals only at higher load level.

Discussion. Experiment 2 aimed to reexamine whether exclusion impaired WM storage capacity. Results showed the CDA amplitude reached asymptote at load 2 for exclusion group and at load 3 for inclusion group, suggesting that excluded individuals reached the upper limit of representation capacity with a smaller memory load than included individuals. In addition, the intergroup comparisons showed that CDA amplitudes were smaller in the excluded group than those in the included group only for memory load 5, but not in loads 1, 2, 3 or 4; these results still existed after we used the difference in CDA amplitude to index storage capacity, as evidenced by smaller index of storage capacity at load 5 (i.e. 2T–5T) for exclusion than for inclusion group but not at load 4 (i.e. 2T–4T), suggesting that excluded individuals were associated with reduced representation capacity relative to included individuals at high, rather than low memory loads.

General discussion

The aim of the present study was to examine whether the poor WM performance caused by social exclusion was due to reduced storage capacity, inability to filtering out task-irrelevant information or both. To investigate this question, we asked excluded participants to perform a lateralized change detection task. In Experiment 1, participants were asked to remember the orientation of red rectangles while ignoring green distractors. Results showed that exclusion impairs attentional filtering ability, as evidenced by the similar CDA amplitudes for 1T1D and 2T conditions, the similar CDA amplitudes for 2T2D and 4T conditions among excluded individuals, as well as smaller index of filtering ability for exclusion than for inclusion group. In Experiment 2, we asked participants to remember 1–5 colored squares. Results showed that exclusion did reduce storage capacity, as the CDA amplitudes reached asymptote at load 2 for exclusion group and at load 3 for inclusion group. Moreover, the reduced representation capacity caused by exclusion was only at high rather than low memory loads. Together, the two experiments provided complementary evidence that excluded participants had impaired attentional filtering ability and reduced storage capacity relative to included individuals.

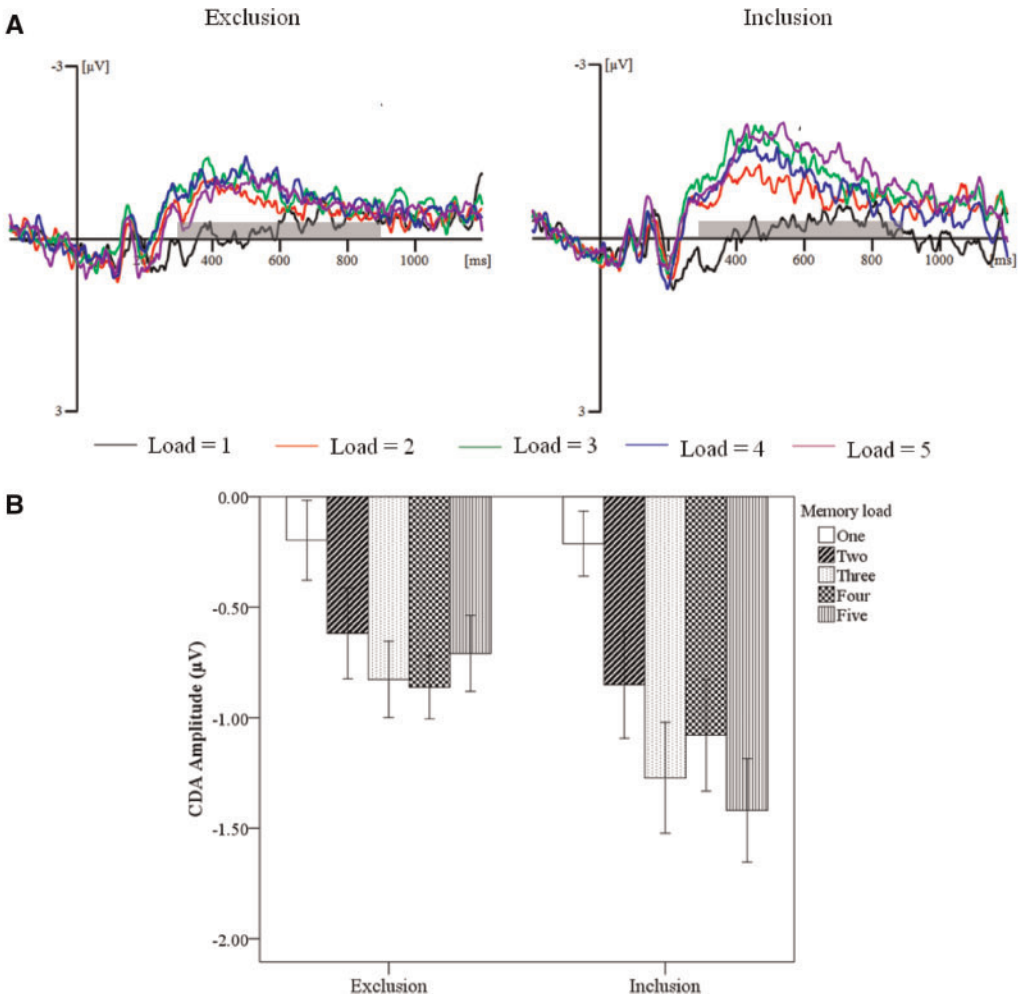

Fig. 4. ERP results in Experiment 2. (A) Grand-average ERP waveforms time-locked to memory array onset showing the contralateral delay activity (CDA) difference waves for each group at each memory load. (B) Mean amplitude of CDA between 300 and 900 ms after memory array onset. Error bars represent SEMs.

Broadly speaking, the general impairment effects of exclusion on filtering ability and reduced storage capacity were consistent with previous studies (Campbell *et al.*, 2006; Chester and DeWall, 2014; Buelow *et al.*, 2015; Xu *et al.*, 2016), and might be relevant to the limitation of attentional resources (Kahneman, 1973). For one thing, according to the Social Monitoring System framework (Gardner *et al.*, 2005), excluded individuals would monitor and maintain their own level of social inclusion by allocating more attentional resources to social-relevant (e.g. smiling face) but less to social-irrelevant information (e.g. stimuli used in present study). For another, based on the self-regulation of affect theory (Baumeister *et al.*, 2002), excluded participants would devote the their own regulatory resources to stifling emotional distress, depleting limited attentional resources. Both the preference of allocating resources to social-relevant information and the self-regulation of exclusion-related negative feelings would restrict the availability of attentional resources for following cognitive control, leading to impaired task performance. Therefore, the deficits in filtering ability and storage capacity in present study might be related to the exhausted attentional resource.

Interestingly, there may be some differences between exclusion's impairments on filtering ability and storage capacity. For the filtering ability (Experiment 1), the detrimental effect of exclusion was more general and was not modulated by task demand/difficulty, covering from easier and lower-level filtering ability (i.e. filter out only one distractor) to harder and higher-level filtering ability (i.e. filter out two distractors). While for the storage capacity (Experiment 2), the impairment effect of exclusion was more specific and was modulated by task demand/difficulty: although exclusion group reached the upper levels of representation capacity with a smaller set size (2 items) compared with the inclusion group (3 items), group differences with regard to CDA could be observed only at high memory loads (5 items) rather than low memory loads (1–4 items). However, one important flaw of current study prevented us from drawing the conclusion that social exclusion differently influences filtering ability and storage capacity. Specifically, these above differences were observed in two studies which were different in both task setting and the complexity of memory materials. That is, while Experiment 1 was design to investigate exclusion's effect on both storage capacity and filtering ability, Experiment 2 was just design to explore exclusion's effect on storage capacity. Besides, while the memory materials were composed of two feature attributes (i.e. colors and orientations) in Experiment 1, the memory materials had only single feature attribute (i.e. colors) in Experiment 2. Thus, we could not directly compare these two studies, and we could not rule out the possibility that these differences ('general' filtering ability impairments and 'specific' storage capacity deficits) were not caused by exclusion, but by the different task setting and the different complexity of memory materials in two experiments. Therefore, further studies are needed to test whether these current results still exist after excluding above-mentioned confounding factors (also see Supplementary material).

Our current conclusions are also restricted by some other limitations. First, because we only included female participants in the current study, our results could not be generalized to male subjects. Although our choice was based on the fact that women have been reported to be more likely to suffer from social exclusion (Benenson *et al.*, 2013), future studies should include both female and male subjects to make a comparison. Second, following previous studies (Vogel *et al.*, 2005; Lee *et al.*, 2010), we hypothesized that WM could be divided into storage capacity and attentional filtering ability. Nevertheless, we acknowledged that these two factors could be interrelated and difficult to separate to some extent. Moreover, in current study, we focused on two components of WM, the storage capacity and the attentional filtering ability. However, some other components could also be important for WM, for instance, the updating ability in WM (Diamond, 2013). Thus future studies should take these points into consideration and conduct more elaborate studies to examine exclusion's impacts on diverse aspects of WM. Third, the current study adopted the Cyberball game to manipulate exclusion, which did not employ a control group. Thus, we cannot fully decipher whether between-group differences were due to an effect within the excluded group, an effect within the included group, or both. Furthermore, although the need threat scores differed between groups, we could not rule out the possibility that participants might tune out during the exclusion condition after they failed to receive the ball in the first few throws. Therefore, future studies should try to avoid these problems. Fourth, as we reported in our results, statistical power (1–β) ranged between 0.05 and 1.00 in the current study (Faul *et al.*, 2007). Although most critical comparisons showed acceptable powers (larger than 0.8), we still acknowledged that the small sample size was a major limitation in current study and should be addressed in future studies. Fifth, as the exclusion's impact could persist only about 50 min (Buelow *et al.*, 2015), to shorten the experiment duration, we manipulated the memory load from 1 to 5 in Experiment 2. However, we agreed that a larger range (e.g. 1–10) was a better choice and might provide us a more comprehensive perspective. Thus, we encourage future studies to test current results with a larger range of memory load. And sixth, in our current study, Experiments 1 and 2 were different in both task setting and the complexity of memory materials. Thus, although our results showed that excluded individuals showed impaired filtering ability (Experiment 1) and storage ability (Experiment 2), we could not combine these results to draw the conclusion that WM deficits caused by exclusion were due to both (and simultaneously) reduced storage capacity and impaired filtering ability. Instead, we could only draw a more prudent conclusion that social exclusion weakens storage capacity and filtering ability in WM. Therefore, future studies should note these limitations and try to address these problems.

In summary, our current study was the first to investigate the neural correlates of WM in exclusion group. ERP data showed that the WM deficits caused by exclusion were due to reduced storage capacity and impaired attentional filtering ability. These results extend our understanding about the relationship between exclusion and executive functions. Specifically, our current findings firstly elucidate the underlying mechanisms of the WM deficits caused by exclusion; and then demonstrate the generality of inhibition control failure in excluded individuals, not only in prepotent response inhibition, but also in the suppression of salient distractors from WM. Finally, the possible different impairment effects of exclusion on filtering ability and storage capacity (i.e. more general for the former, and more specific for the latter) add to the increasing evidences to highlight that exclusion exerts more complex influences on executive functions (Shilling and Brown, 2016; Xu *et al.*, 2016), thus calling for more studies to explore this issue.

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Supplementary data

Supplementary data are available at *SCAN* online.

Conflict of interest. None declared.

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