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ORIGINAL ARTICLE

Gestalt grouping cues can improve filtering performance in visual working memory

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Abstract

As part of filtering irrelevant information from entering visual working memory (VWM) and selecting only the relevant information for further processing the system should first tag the pieces of information as relevant or irrelevant. We manipulated difficulty of tagging items as relevant or irrelevant by applying perceptual grouping cues to investigate if it can improve filtering performance in VWM. Participants performed a change-detection task with three targets, six targets, or three targets and three distractors (filtering condition) in the memory display, and were asked to remember the colors (Experiments 1–2) or the orientations (Experiments 3–5) of the targets and ignore the distractors. In the filtering conditions, either the targets (Experiments 1, 3, and 4) or the distractors (Experiments 2 and 5) formed an illusory object (a Kanizsa triangle), appeared in a triangle-like configuration (grouping by proximity), or appeared at random positions (non-grouping). Grouping the targets improved filtering performance relative to non-grouping. Moreover, the illusory object cue further improved filtering performance beyond a proximity cue, but only when the cue was compatible with the task. When the distractors were grouped, the proximity cue improved filtering performance, and the illusory object cue, despite being a potent grouping cue, failed to improve filtering performance when it was compatible with the task. We suggest that the grouping cues advanced tagging of the grouped items. Yet, when the grouping cue strongly enhanced processing of the distractors, the tagging failed, such that the preliminary process of estimating incoming items led to full processing of the grouped items.

Introduction

Visual working memory (VWM) is our temporary buffer that can hold a limited amount of information in an active "online" state (for a review see Luck & Vogel, 2013). One primary characteristic of VWM is its highly limited capacity, and many studies suggested that VWM has a capacity limit of about 3–4 objects (Awh, Barton, & Vogel, 2007; Cowan, 2001; Luck & Vogel, 1997; Pashler, 1988; Vogel & Machizawa, 2004; Vogel, Woodman, & Luck, 2001; Xu & Chun, 2006; Zhang & Luck, 2008). Nevertheless, there are robust individual differences in VWM capacity (e.g., Vogel & Awh, 2008), and studies have shown that these individual differences predict performance in a variety of aptitude measures. For example, high-capacity individuals tend to get higher scores in fluid intelligence measures and in complex cognitive tasks such as verbal learning and problem solving compared to their low-capacity counterparts (Cowan et al., 2005; Cowan, Fristoe, Elliott, Brunner, & Saults, 2006; Fukuda, Vogel, Mayr, & Awh, 2010; Johnson et al., 2013; Unsworth, Fukuda, Awh, & Vogel, 2014, 2015). Furthermore, impairments in VWM functioning were associated with old age (Cashdollar et al., 2013) and with psychiatric disorders such as Schizophrenia (Gold et al., 2006; Gold, Wilk, McMahon, Buchanan, & Luck, 2003) and Alzheimer's disease (Parra et al., 2009, 2010). These findings indicate that VWM plays an important role in guiding behavior. Therefore, researchers have tried to characterize the available mechanisms that provide VWM the desired means to deal with such extreme limitations in its capacity.

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What has emerged as a primary mechanism for dealing with capacity limitations in VWM is the ability to properly allocate attentional resources to select only task-relevant information to enter VWM and to filter out irrelevant information from entering the limited VWM workspace (Allon & Luria, 2017; Arnell & Stubitz, 2010; Awh & Vogel, 2008; Fukuda & Vogel, 2009, 2011; Gaspar, Christie, Prime, Jolicœur, & McDonald, 2016; Jost, Bryck, Vogel, & Mayr, 2011; Jost & Mayr, 2016; Li, He, Wang, Hu, & Guo, 2017; McNab & Dolan, 2014; McNab & Klingberg, 2008; Owens, Koster, & Derakshan, 2012; Vogel & Awh, 2008; Vogel, McCollough, & Machizawa, 2005). Furthermore, studies suggested that filtering ability underlies individual differences in VWM capacity (e.g., Fukuda & Vogel, 2009; McNab & Klingberg, 2008; Vogel et al., 2005). Namely, high-capacity individuals are better able to control what is encoded in their VWM relative to low-capacity individuals, successfully ignoring irrelevant information and encoding only the task-relevant information. These studies suggested that the filtering mechanism acts as a gateway to VWM intended to select only the task-relevant information. However, attentional resources can be involuntarily allocated to stimuli in the environment, even if they are irrelevant to the current task, resulting in a decrement in task performance. Since the filtering mechanism is an attentional mechanism, in the current study we refer to its end result (i.e., the observed accuracy in a VWM task) as 'filtering performance'.

For example, Vogel et al. (2005) presented participants with memory arrays of either two relevant items, four relevant items (i.e., non-filtering conditions), or two relevant items with two irrelevant task items (i.e., the filtering condition). Using a neural index for the number of items maintained in VWM (for a review see Luria, Balaban, Awh, & Vogel, 2016; Vogel & Machizawa, 2004), Vogel et al. showed that low-capacity individuals represented also the task irrelevant items such that their neural measure of the filtering condition was similar to the four relevant items condition, indicating poor filtering. Conversely, the neural measure of the filtering condition for high-capacity individuals was similar to the two relevant items, indicating better filtering abilities. Other studies using a behavioral measure for filtering performance (Allon & Luria, 2017; Arnell & Stubitz, 2010; Fukuda & Vogel, 2009; Li et al., 2017), corroborated this pattern by showing that low-capacity individuals had lower filtering performance relative to high-capacity individuals, such that the difference in accuracy rate between the non-filtering condition and the filtering condition was larger for low-capacity individuals relative to high-capacity individuals. These findings indicate that filtering ability is a key mechanism in effective VWM functioning.

Filtering is a complex mechanism, consisting of multiple sub-processes. Before triggering any filtering processes, the system has to first distinguish between the relevant and the irrelevant information, to suppress only the irrelevant information. Thus, it is imperative to note that our system must process all information to some degree, until it can differentiate pieces of information by tagging them with the appropriate label (i.e., relevant or irrelevant), and then try to stop processing the information that was tagged as irrelevant (Sawaki, Geng, & Luck, 2012; Sawaki & Luck, 2010, 2011) while selecting only the information that was tagged as relevant for further processing. For example, using an electrophysiological measure for distractor suppression (Hickey, Di Lollo, & McDonald, 2009), Sawaki and Luck (2010) have shown that a silent singleton is detected by the system although it did not necessarily capture attention, supporting the notion that irrelevant information is processed to some degree, at least until it is tagged as irrelevant. As processing progresses, it becomes more difficult to stop and ignore the already processed information, and from this point of view, it is not surprising that our filtering ability is not perfect.

In the current study, we investigated the tagging process, assuming tagging is an initial and essential process in triggering later processing stages of the filtering mechanism. Therefore, we reasoned that manipulating the tagging difficulty should affect filtering performance in VWM. A possible candidate for improving the tagging of items as relevant or irrelevant, and by that boosting filtering performance, is using grouping cues to parse and organize small pieces of information in the visual scene into integrated units of information (e.g., Neisser, 1967; Treisman, 1982). Previous studies have shown that Gestalt grouping cues enhance perceptual processing (e.g., Baylis & Driver, 1992; Duncan, 1984; Kimchi, Yeshurun, & Cohen-Savransky, 2007; Kimchi, Yeshurun, Spehar, & Pirkner, 2016; for a review see Wagemans et al., 2012), suggesting that Gestalt grouping cues operate in relatively early processing stages. Thus, Gestalt grouping hold the potential to improve the tagging of incoming items as targets or as distractors, because these items could be tagged together as a group. This should enhance the differentiation and the separation between the relevant and the irrelevant information, and in turn, could help the filtering mechanism to filter out the items tagged as irrelevant and select only the relevant information for further processing, resulting in better filtering performance.

Previous studies validated that grouping the targets improves VWM performance (Gao et al., 2011; Gao, Gao, Tang, Shui, & Shen, 2016; Luria & Vogel, 2014; Peterson & Berryhill, 2013; Peterson, Gözenman, Arciniega, & Berryhill, 2015; Shen, Yu, Xu, & Gao, 2013). Nevertheless, the question of whether perceptual grouping affects filtering ability was never investigated. Note that in previous studies who investigated how perceptual grouping affects VWM performance, participants were asked to remember all the items that appeared in the memory array. The reason is that in these studies irrelevant items were not presented in the display. Additionally, note that previous studies that investigated how the filtering mechanism affects VWM performance (e.g., Vogel et al., 2005), did not apply grouping principles in the memory array. For the current purpose, this means that previous research either focused on how perceptual grouping affects VWM performance by providing grouping cues without including irrelevant items in the display in addition to the relevant items, or focused on how the filtering mechanism affects VWM performance by presenting relevant and irrelevant items without applying grouping principles in the display.

In the current work, we manipulated the difficulty of the tagging process in five experiments and investigated how the tagging difficulty affected filtering performance. Participants performed a change-detection task in which either three targets (3T), six targets (6T), or three targets along with three distractors (i.e., the filtering condition; 3T3D) appeared in the memory array, and were asked to remember the colors (Experiment 1 and Experiment 2) or the orientations of the targets (Experiment 3, Experiment 4, and Experiment 5). In the filtering conditions, the targets (Experiments 1, Experiment 3, and Experiment 4) or the distractors (Experiment 2 and Experiment 5) either formed an illusory object in the shape of a Kanizsa triangle (Kanizsa, 1976; grouping by an illusory object), appeared in a triangle-like configuration (grouping by proximity), or appeared at random positions (non-grouping; see 3T3D illusory object, 3T3D proximity, and the 3T3D random conditions in Fig. 1a for an example). Previous studies have indicated that an illusory object cue is a very strong grouping cue in guiding the processing stream (Davis & Driver, 1994; Fahrenfort, van Leeuwen, Olivers, & Hogendoorn, 2017; Kimchi et al., 2007, 2016; Wang, Weng, & He, 2012; but see Harris, Schwarzkopf, Song, Bahrami, & Rees, 2011; Moors, Wagemans, van Ee, & de-Wit, 2016). Therefore, this allowed us to investigate whether the tagging process is also sensitive to the strength of the grouping cue, such that accuracy in the illusory object condition will be different than the accuracy in the proximity condition.

Based on previous findings (e.g., Richard, Lee, & Vecera, 2008; Woodman, Vecera, & Luck, 2003), we predicted that grouping the targets will improve VWM performance in the filtering condition (i.e., filtering performance). Specifically, we predicted that accuracy in the filtering conditions in which the targets were grouped will be higher than accuracy in the non-grouping filtering condition. This is because the grouped targets will be better detected due to their improved tagging, biasing their entrance into VWM.

As for grouping the distractors, previous findings (e.g., Gaspar et al., 2016; Gulbinaite, Johnson, de Jong, Morey, & van Rijn, 2014) provided support that effective VWM filtering relies on the ability to suppress distractors instead of enhancing the target processing. Moreover, in a recent study (Allon & Luria, 2017), we showed that cueing the distractors via a combined spatial and temporal cue improved filtering performance in VWM. Hence, one option is that grouping the distractors holds the potential to improve filtering performance in VWM. A possible reason is that grouping would help the filtering mechanism reject the grouped distractors as an integrated group (a process previously termed spreading suppression; Dent, Humphreys, & Braithwaite, 2011; Humphreys, Quinlan, & Riddoch, 1989). On the other hand, grouping the distractors might interfere with the filtering mechanism, when Gestalt grouping cues strongly bias processing the distractors. The reason is that previous studies have shown that Gestalt grouping cues can cause processing enhancement to the extent that illusory objects formed by Gestalt grouping cues capture attention irrespective of the task demands (e.g., Kimchi et al., 2007, 2016). Thus, the initial process of evaluating incoming items could lead to

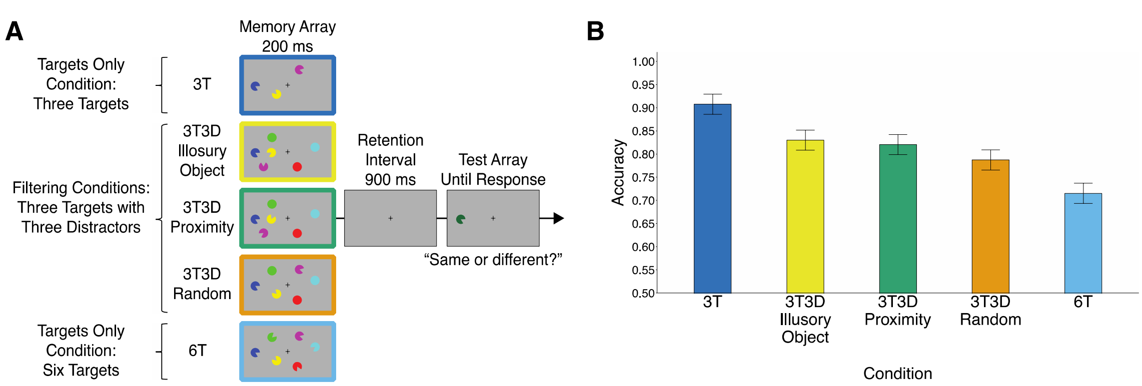

Fig. 1 **a** Example of targets only trials (i.e., three targets or six targets) and filtering trials (i.e., three targets along with three distractors) in Experiment 1. Participants were asked to remember all the colors of the circles with a triangle opening (targets) and ignore the other circles (distractors). In the filtering conditions, the targets either formed a Kanizsa triangle (grouping by an illusory object), appeared in a configuration of a triangle (grouping by proximity), or appeared in random positions (non-grouping). **b** Results from Experiment 1. Accuracy as a function of condition. Error bars represent 95% confidence intervals according to Loftus and Masson (1994)

full processing of irrelevant information when processing Gestalt items is too fast to be stopped, which might interfere with target processing. Therefore, we did not have an a priori prediction as for grouping the distractors. To test the extent to which filtering performance was affected by the grouping cues, we also compared accuracy performance between the 3T and the 3T3D grouping conditions.

Experiment 1

In Experiment 1, we examined whether an illusory object grouping cue and a proximity grouping cue that are applied on the targets can improve tagging of items as relevant, thereby boosting the filtering performance in VWM. Participants viewed memory arrays with colored circles that had a triangle opening (that served as targets), and complete colored circles (that served as distractors). The memory arrays included either 3T, 6T, or 3T3D, and participants were asked to remember the targets' colors (i.e., circle with an opening) and ignore the distractors (i.e., the colored circles; see Fig. 1a). A short delay followed the memory array, followed by a test probe that appeared in one of the locations of the targets in the memory array. The task was to indicate whether the test probe was in the same color as the color of the target that appeared at the same position in the memory array. In the filtering condition the targets either formed a Kanizsa triangle (3T3D illusory object), appeared in a triangle-like configuration (3T3D proximity), or appeared at random positions (i.e., non-grouping condition; 3T3D random), which did not encourage grouping. In the illusory object condition, the targets were in the same spatial distance from one another as the targets in the proximity condition. We tested whether performance in the filtering condition (illusory object and proximity) is affected by the grouping cues relative to filtering performance in the non-grouping condition, resulting in improved accuracy performance. In addition, we also tested whether the formation of the Kanizsa triangle in the illusory object condition further affected filtering performance, beyond proximity, assuming an illusory object is a very strong grouping cue (Davis & Driver, 1994; Fahrenfort et al., 2017; Kimchi et al., 2007, 2016; Wang et al., 2012).

Method

Participants

Twenty-four students from Tel Aviv University (21 females, *M* 23 years, SD 2.1) participated in the experiment. Each of the five experiments took 45 min for either course credit or payment of 30 shekels (about 8$). Participants in all five experiments gave their informed consent after the procedures of a protocol approved by the Ethics Committee at Tel Aviv University. Participants in all five experiments had normal or corrected-to-normal visual acuity and reported normal color-vision.

Apparatus

Stimuli were presented on 23-in. light emitting diode backlight liquid crystal display monitor with a 120 Hz refresh rate, using 1920 × 1080 resolution graphics mode. Participants were seated approximately 60 cm from the monitor.

Stimuli and procedure

Filtering change-detection task

Participants performed a change-detection task (e.g., Luck & Vogel, 1997) in which they were presented with a black fixation cross (i.e., "+") for 500 milliseconds (ms), followed by an array of colored circles with a triangle opening (i.e., targets) in different orientations (i.e., in 1 of 12 orientations starting from 0° in increments of 30° chosen randomly without replacement) for 200 ms (memory array), and were asked to remember only the colors of the targets. Then, the memory array disappeared for 900 ms (retention interval); followed by the test array in which one target (a test probe) appeared at one of the previous locations of the targets in the memory array. Participants made an unspeeded response via button press ("Z" and "/" on the computer keyboard, counterbalanced across participants) to indicate whether the color of the test probe was the same as the color of the target in the memory array (with equal probability for same and different test probes). Participants were informed that only the color of the target could change, and that the orientation of the test probe was always the same as the orientation of the target that appeared at that location in the memory array. On about a third of the trials, three targets were presented along with three colored circles served as distractors, (i.e., the filtering condition). On the rest of the trials, arrays of either three or six targets were presented (targets only conditions). All stimuli had a radius of approximately 0.76° of visual angle, and the triangle opening of the target was a sixth of its size. All stimuli were randomly positioned within a 19.85° × 19.85° region of visual angle on the video monitor upon a gray background with the constraint that the minimal distance between each two stimuli was at least 2.85° of visual angle (center to center). The color of each stimulus was randomly selected without replacement from a set of eight colors: dark green, blue, cyan, green, pink, red, brown, and yellow. On changed trials the changed item was replaced with a color not presented in the memory array. The probability for each of the three conditions (i.e., 3T, 3T3D, 6T) was one-third, such that each of them appeared in about 180 trials. A total of 540 trials were presented in nine intermixed blocks of 60 trials each. To group the targets, in the filtering condition the targets either formed a Kanizsa triangle (3T3D illusory object), appeared in a triangle-like configuration (3T3D proximity), or appeared at random positions (3T3D random; with equal probability for each of the three filtering conditions, resulting in about 60 trials for each of the filtering conditions; see Fig. 1a). Each side of the Kanizsa triangle in the illusory object condition subtended approximately 3.6° of visual angle. Note that the difference between the illusory object and the proximity cue condition was that in the illusory object condition the targets formed the Kanizsa triangle whereas in the proximity condition the targets appeared in a triangle-like configuration without forming a Kanizsa triangle. Participants were told that the targets could form a Kanizsa triangle, were shown an example of a Kanizsa triangle, and were told that in any case they should concentrate on remembering the colors of the targets and ignore the distractors, independently of how the targets appeared. Ten practice trials were given before starting the experiment.

In all five experiments, invalid trials (i.e., trials with RTs lower than 100 ms or higher than 2000 ms) were removed from further analysis (resulting in the removal of 3.77, 2.45, 3.37, 5.71, and 6.49% of the trials in Experiment 1, Experiment 2, Experiment 3, Experiment 4, and in Experiment 5, respectively), and then mean accuracy rates were calculated for each participant and for each combination of the independent variables to allow statistical analysis. This data preparation was conducted using *prepdat*—an *R* package for preparing experimental data for statistical analysis (Allon & Luria, 2016).

Visual working memory capacity estimates: change-detection task

Before the filtering change-detection task participants performed a change-detection task with colored squares (e.g., Fukuda & Vogel, 2009) to estimate their VWM capacity as part a standard procedure in the beginning of an experiment in the lab. Participants were presented with arrays of four or eight colored squares for 150 ms (memory array); the squares then disappeared for 900 ms (retention interval), and then a colored square (a test probe) appeared at one of the previous locations of the items in the memory array. Participants made an unspeeded response via button press ("Z" and "/" on the computer keyboard, counterbalanced across participants) to indicate whether the color of the test probe was the same as the color of the square that appeared at the same location in the memory array (with equal probability for same and different test probes). Sixty trials were presented for each array size in one intermixed block. Each color square subtended approximately 1.24° × 1.24° of visual angle and was randomly positioned within a 16.6° × 16.6° region on the video monitor upon a gray background with the constraint that the minimal distance between every two stimuli was at least 2° of visual angle (center to center). The color of each square was randomly selected (without replacement) from a set of nine colors: black, blue, brown, cyan, green, orange, pink, red, and yellow. On changed trials the changed item was replaced with a color not presented in the memory array. The accuracy for each individual was transformed into a *K* estimate (separately for each set-size) following standard formula (Cowan, 2001; Pashler, 1988). The formula is $K = S \times (H - F)$, where K is the memory capacity, S is the size of the memory array, H is the observed hit rate, and F is the false alarm rate. These two values were averaged to form a single VWM capacity estimate (K). We did not find consistent correlations between K and estimates of filtering across experiments and, therefore, we do not further report this measure. These correlations can be found in Fig S1 in the Supplementary Material.

Results and discussion

Filtering change-detection task

Repeated measures analysis of variance (ANOVA) with condition (3T, 3T3D Illusory object, 3T3D proximity, 3T3D random, 6T) on accuracy rates as a dependent variable showed a main effect of condition [$F(4, 92) = 43.80$, MSE 0.00267, $p < 0.001$, $\eta_p^2 = 0.65$; see Fig. 1b]. Planned comparisons corrected to FDR p value of 0.0333 (Benjamini & Hochberg, 1995) showed that accuracy in the 3T3D illusory object condition (*M* 0.83, SD 0.10) was not different than accuracy in the 3T3D proximity condition (*M* 0.82, SD 0.08; $F < 1$). Therefore, all further comparisons were performed across the two grouping conditions (forming a single grouping condition). Importantly, the accuracy in the grouping conditions (*M* 0.82, SD 0.09) was higher than accuracy in the 3T3D random condition (*M* 0.78, SD 0.11), a difference that was marginally significant [$F(1, 23) = 5.00$, MSE 0.004587, $p = 0.0352$, $\eta_p^2 = 0.17$], indicating that grouping was able to improve the filtering performance. In addition, accuracy in the 3T condition (*M* 0.90, SD 0.06) was higher than accuracy in the grouping conditions [*M* 0.82, SD 0.09; $F(1, 23) = 45.35$, MSE 0.002393, $p < 0.001$, $\eta_p^2 = 0.66$], indicating that although grouping the targets improved filtering performance, filtering performance was not as good as performance in the 3T condition, and that the distractors were processed to some extent.

The results of the current experiment demonstrate that Gestalt grouping cues implemented on the targets were able to improve filtering performance in VWM relative to a condition in which no-grouping was encouraged. These findings suggest that grouping the relevant information can bias the entrance of the grouped items into VWM, in accordance with previous findings (e.g., Peterson & Berryhill, 2013; Woodman et al., 2003). We suggest that since Gestalt grouping cues are known to enhance perceptual processing (e.g., Wagemans et al., 2012), this perceptual enhancement improved tagging of the items that appeared in proximity to each other as targets. This in turn helped to separate between the targets and the distractors, resulting in better filtering performance, because the grouped items were better detected.

Despite previous findings suggesting that an illusory object grouping cue is a very efficient cue (e.g., Fahrenfort et al., 2017), an illusory object cue in which the targets formed a Kanizsa triangle did not further improve filtering performance relative to a condition in which the illusory object was not formed. A possible explanation for this similar performance comes from a study by Poljac, de-Wit, and Wagemans (2012), who showed reduced accessibility to the changing parts of illusory objects when color was the relevant task dimension. Therefore, it could be that perceiving the Kanizsa triangle resulted in the inability to properly report whether one of its inducers (i.e., the test probe) has changed. In the next experiment, we tested whether implementing the same grouping cues (i.e., illusory object and proximity) on the distractors will affect filtering performance as well.

Experiment 2

The goal of Experiment 2 was to see whether an illusory object grouping cue and a proximity grouping cue that are applied on the distractors can affect tagging of the items as irrelevant, thereby affecting filtering performance in VWM. Participants performed a similar task to the one used in Experiment 1. However, this time the circles served as targets and the circles with a triangle opening served as distractors. In the filtering condition the distractors either formed a Kanizsa triangle (illusory object), appeared in a triangle-like configuration (proximity), or appeared at random positions (random), which did not encourage grouping (see Fig. 2a).

Method

Participants

Twenty-four students from Tel Aviv University (18 females, *M* 25 years, SD 2.22) participated in the experiment.

Apparatus

The same apparatus was used as in Experiment 1.

Stimuli and procedure

Filtering change-detection task

Participants performed a change-detection task similar to the one in Experiment 1 except for the following. Participants were presented with memory arrays of colored circles (targets) and were asked to remember the colors of the circles. A retention interval followed the memory array, followed by a test probe that appeared at one of the previous locations of the targets in the memory array. Participants indicated whether the test probe was in the same or different color as the target in that location that appeared in the memory array. On about a third of the trials, three targets were presented along with three colored circles with a triangle opening used as distractors, (i.e., 3T3D; the filtering condition). On the rest of the trials, arrays of either three (3T) or six (6T)

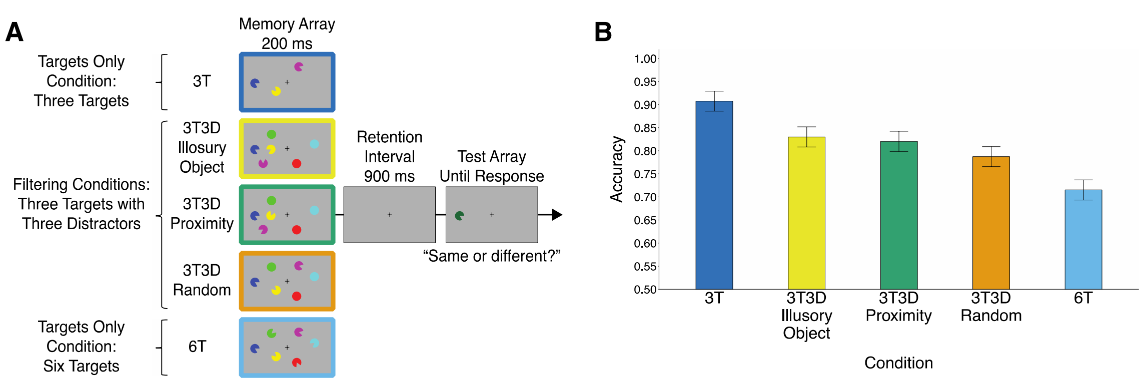

Fig. 2 **a** Example for targets only trials and filtering trials in Experiment 2. Participants were asked to remember all the colors of the circles (targets) and ignore the circles with a triangle opening (distractors). The distractors either formed a Kanizsa triangle (grouping by illusory object), appeared in a configuration of a triangle (grouping by proximity), or appeared in random positions (no-grouping). **b** Results from Experiment 2. Accuracy as a function of Condition. Error bars represent 95% confidence intervals according to Loftus and Masson (1994)

targets were presented (targets only conditions; see Fig. 2a). The probabilities for each of the conditions was the same as in Experiment 1. To group the distractors, in the filtering conditions the distractors either formed a Kanizsa triangle (3T3D illusory object), appeared in a triangle-like configuration (3T3D proximity), or appeared at random positions (3T3D random). Participants were told that the distractors could form a Kanizsa triangle, were shown an example of a Kanizsa triangle, and that in any case they should concentrate on remembering the colors of the targets and ignore the distractors, independently of how the distractors appeared.

Visual working memory capacity estimates: change-detection task

Participants performed the change-detection task as in Experiment 1.

Results and discussion

Filtering change-detection task

A repeated measures ANOVA was conducted as in Experiment 1. The ANOVA showed a main effect of condition [$F(4, 92) = 75.31$, MSE 0.00172, $p < 0.001$, $\eta_p^2 = 0.76$; see Fig. 2b]. Planned comparisons corrected to FDR p value of 0.0333 (Benjamini & Hochberg, 1995) showed that accuracy in the 3T3D illusory object condition (M 0.84, SD 0.08) was not different than accuracy in the 3T3D proximity condition (M 0.83, SD 0.08; $F < 1$). Therefore, all further comparisons were performed across the grouping conditions (forming a single grouping condition). Importantly, planned comparison showed that accuracy in the grouping conditions (M 0.84, SD 0.08) was higher than the accuracy in the 3T3D random condition [M 0.80, SD 0.09; $F(1, 23) = 12.79$. MSE 0.001673, $p = 0.001596$, $\eta_p^2 = 0.17$]. This indicates that grouping cues implemented on the distractors were able to improve filtering performance in VWM. In addition, accuracy in the 3T condition (M 0.90, SD 0.07) was higher than accuracy in the grouping condition [M 0.84, SD 0.08; $F(1, 23) = 48.21$, MSE 0.00163, $p < 0.001$, $\eta_p^2 = 0.67$], suggesting that the distractors were processed to a certain degree.

The results of the current experiment indicate that grouping the distractors can improve rejection of those distractors from entering VWM, possibly by enhancing the separation process between the relevant and the irrelevant items. We suggest this separation enhancement occurred due to better tagging of the grouped items, which enabled the filtering mechanism to reject the distractors as an integrated group. This result corroborates previous findings who found that cuing the distractors can improve filtering performance in VWM (Allon & Luria, 2017). In addition, an illusory object grouping cue in which the distractors formed a Kanizsa triangle, keeping the same proximity and spatial distance between the items as in the proximity grouping cue, did not further improve filtering performance. These results replicate the findings from Experiment 1, but are rather surprising given that previous findings demonstrated how unique and potent is an illusory object when processing information (e.g., Fahrenfort et al., 2017; Schwarzkopf & Rees, 2015).

Note that in the proximity condition in both Experiment 1 and in Experiment 2, it is possible that a similarity grouping cue also contribute to performance. This is because the targets had an entirely different shape than the distractors, and the distractors were similar in shape to each other, enabling participants to group the targets (distractors) by their shape. In addition, note that in both Experiment 1 and in Experiment 2 the relevant task dimension was the targets' colors, whereas the targets and distractors orientations were completely irrelevant for successful performance. Yet, the Kanizsa triangle is formed by the spatial configuration of the orientations of the circles with a triangle opening. Furthermore, the Kanizsa triangle was composed of items in different colors, which did not create the ideal contrast to perceive the illusory Kanizsa triangle (Spehar, 2000; Spehar & Clifford, 2003). Therefore, it might be that in Experiments 1 and 2 the illusory object grouping cue did not further improve filtering performance because the task (i.e., the use of different colors and a task that required to remember the colors) was not compatible with the properties of the Kanizsa triangle. In the next experiments, we tested whether using a task which is compatible with the illusory object cue will improve filtering performance in the illusory object condition beyond the proximity condition.

Experiment 3

While Experiments 1 and 2 provided compelling evidence that grouping can improve filtering performance presumably by supporting the tagging process, both the illusory object and the proximity cues had similar effects on performance, even though an illusory object is considered a stronger and more efficient grouping cue. In Experiment 3 we examined whether an illusory object cue applied on the targets will improve filtering performance beyond the proximity cue when using a task that was compatible with the formation of the Kanizsa triangle.

To this end, in Experiment 3 the task required to remember the orientations of the targets, because this dimension is also the one responsible for forming the Kanizsa triangle. Furthermore, we dropped the colors of the stimuli to increase the perception of the Kanizsa triangle. Participants performed a similar task to the one used in Experiment 1. However, this time all the items in the display were white and participants were asked to remember the orientations of the circles with a triangle opening (i.e., targets) and ignore the circles with a rectangle opening (i.e., distractors; see Fig. 3a).

Method

Participants

Twenty-four students from Tel Aviv University (20 females, *M* 23 years, SD 2.19) participated in the experiment. One subject was excluded from analysis due to below chance accuracy rates in the change-detection task.

Apparatus

The same apparatus was used as in Experiment 1.

Stimuli and procedure

Filtering change-detection task

Participants performed a change-detection task similar to the one in Experiment 1 except for the following. Participants were presented with memory arrays of white circles with a triangle opening in different orientations and were asked to remember the orientations of these stimuli (targets). Participants indicated whether the test probe was in the same or in a different orientation as the orientation of the target that appeared at that location in the memory array. About a third of the trials were 3T3D trials, in which three targets were presented along with three white circles with a rectangle opening used as distractors. On the rest of the trials, arrays of either 3T or 6T targets were presented (targets only conditions; see Fig. 3a). The probabilities for each of the conditions was the same as in Experiment 1. All stimuli had a radius of approximately 0.76° of visual angle, and the rectangle opening of the distractors was approximately 1° × 0.7° of visual angle. The targets and the distractors appeared in different orientations as in Experiment 1, and on changed trials the changed item was replaced with an orientation not presented in the memory array. To group the targets, in the filtering condition the targets either formed a Kanizsa triangle (3T3D illusory object), appeared in a triangle-like configuration (3T3D proximity), or appeared at random positions (3T3D random). Participants were told that the targets could form a Kanizsa triangle, were shown an example of a Kanizsa triangle, and were told that in any case they should concentrate on remembering the orientations of the targets and ignore the distractors, independently of how the targets appeared.

Visual working memory capacity estimates: change-detection task

Participants performed the change-detection task as in Experiment 1.

Results and discussion

Filtering change-detection task

Repeated measures ANOVA was conducted as in Experiment 1. The ANOVA showed a main effect of condition [$F(4, 92) = 41.26$, MSE 0.00363, $p < 0.001$, $\eta_p^2 = 0.64$; see Fig. 3b]. Planned comparisons corrected to FDR *p* value of 0.05 (Benjamini & Hochberg, 1995) showed that accuracy in the 3T3D illusory object condition (*M* 0.77, SD 0.10) was higher than accuracy in the 3T3D proximity condition [*M* 0.64, SD 0.07; $F(1, 23) = 37.05$, MSE 0.005372, $p < 0.001$, $\eta_p^2 = 0.61$]. This result indicates that when the task was

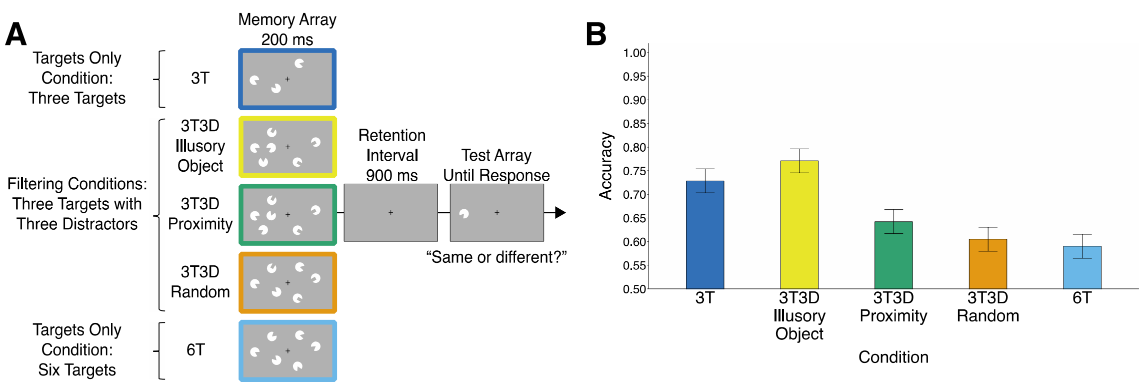

Fig. 3 **a** Example for a targets-only (i.e., three targets or six targets) and filtering trials (i.e., three targets along with three distractors) in Experiment 3. Participants were asked to remember the orientations of the circles with a triangle opening and ignore the circles with a rectangle opening. To group the targets in the filtering conditions, the targets either formed a Kanizsa triangle (grouping by illusory object), appeared in a configuration of a triangle (grouping by proximity), or appeared in random positions (no-grouping). **b** Results from Experiment 3. Accuracy as a function of condition. Error bars represent 95% confidence intervals according to Loftus and Masson (1994)

compatible with the properties of the Kanizsa triangle, the illusory object cue was able to improve filtering performance beyond the proximity cue. Moreover, accuracy in the 3T3D illusory object condition (*M* 0.77, SD 0.10) was even higher than accuracy in the 3T condition [*M* 0.72, SD 0.07; $F(1, 23) = 9.73$, MSE 0.002226, $p = 0.004$, $\eta_p^2 = 0.29$]. But, note that targets in the 3T condition were arranged randomly while targets in the 3T3D illusory object condition formed a Kanizsa triangle, which is probably why performance in the 3T3D illusory object condition was higher (see below). As for the 3T3D proximity condition (*M* 0.64, SD 0.07), accuracy was higher than accuracy in the 3T3D random condition [*M* 0.60, SD 0.06; $F(1, 23) = 5.01$, MSE 0.003296, $p = 0.0350$, $\eta_p^2 = 0.17$]. This suggests that a proximity grouping cue alone was able to improve filtering performance, replicating the results from Experiment 1.

The findings from the present experiment support previous studies demonstrating the superiority of an illusory object grouping cue relative to other grouping cues (e.g., Kimchi et al., 2007, 2016; Wang et al., 2012). We suggest that the illusory object cue in the current experiment was more salient than the illusory object cue in Experiments 1 and 2 due to the compatibility of the task with the illusory object cue and higher contrast polarity resulting from the items being in the same color. This resulted in better tagging of the targets in the illusory object cue relative to the proximity cue, thus enhancing the separation between the targets and the distractors, biasing the entrance of the grouped targets into VWM.

Interestingly, performance in the 3T3D illusory object condition (that included distractors) was even higher than performance in the 3T condition (that included only targets). Namely, performance in a condition that involved filtering distractors was even better than a condition with only targets. However, note that the 3T included ungrouped targets, while the filtering condition included both distractors and a grouping cue (because targets formed a Kanizsa triangle). Therefore, we assume that comparing the 3T and the 3T3D grouped condition in the current experiment (and in Experiment 1) might resulted in an underestimation of the difference between the 3T and each of the 3T3D grouped conditions. In Experiment 4, we applied the grouping cues also on the 3T condition to enable an appropriate estimation of the degree to which the grouping cues improve filtering performance.

Experiment 4

The goal of Experiment 4 was to manipulate the tagging difficulty also in the 3T condition to allow an appropriate estimation of the extent to which the grouping cues used in Experiment 3 improve filtering performance. To this end, participants performed a change-detection task similar to the one in Experiment 3. However, this time we used only the 3T and 3T3D conditions. Importantly, in both the 3T and the 3T3D conditions the targets could either form a Kanizsa triangle (illusory object), appear in a configuration of a triangle (proximity), or appeared at random positions (random; see Fig. 4a), forming a factorial within-subjects design with trial-type (3T, 3T3D) and grouping (illusory object, proximity, random). Thus, if the grouping cues improve filtering performance such that the distractors are completely excluded from entering VWM, then performance

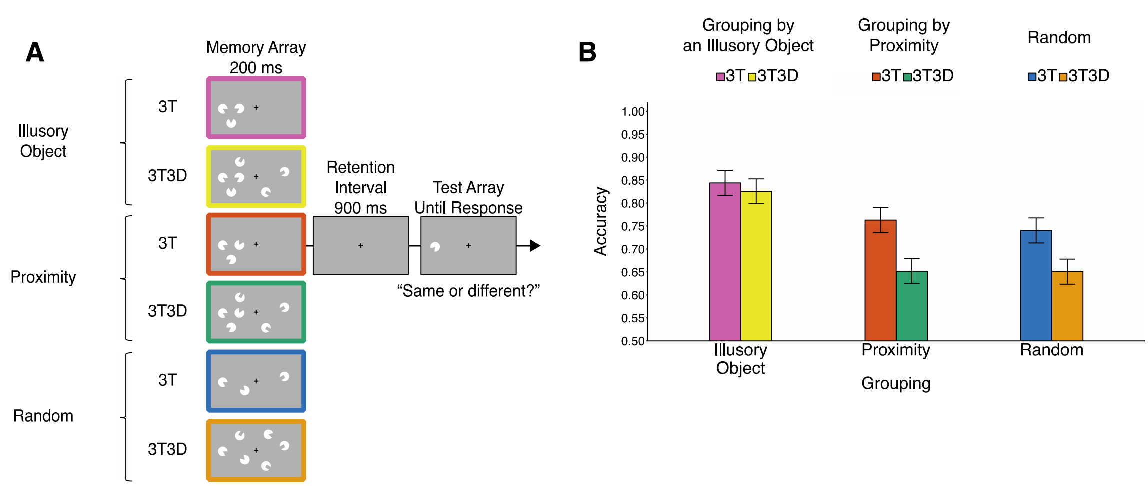

Fig. 4 **a** Example for targets-only (i.e., three targets) and filtering trials (i.e., three targets along with three distractors) in Experiment 4. Task was the same as in Experiment 3. To group the targets, the targets either formed a Kanizsa triangle (grouping by illusory object), appeared in a configuration of a triangle (grouping by proximity), or appeared in random positions (no-grouping). **b** Results from Experiment 4. Accuracy as a function of grouping and trial-type. Error bars represent 95% confidence intervals according to Loftus and Masson (1994)

in the 3T3D illusory object condition should be similar to performance in the 3T illusory object condition, and performance in the 3T3D proximity condition should be similar to performance in the 3T proximity condition. Conversely, if the grouping cues improve filtering performance only partially, then performance in the 3T3D illusory object condition should be smaller than performance in the 3T illusory object, and the similar logic applies for the 3T3D proximity and 3T proximity conditions.

In addition, replicating the results of Experiment 3, we predicted higher filtering performance in the 3T3D illusory object condition relative to the 3T3D proximity condition. Furthermore, we predicted better filtering performance in the 3T3D proximity condition relative to the 3T3D random condition.

Method

Participants

Twenty-four students from Tel Aviv University (19 females, *M* 26.1 years, SD 4.62) participated in the experiment.

Apparatus

The same apparatus was used as in Experiment 1.

Stimuli and procedure

Filtering change-detection task

Participants performed a change-detection task similar to the one in Experiment 3 except for the following. On about two-thirds of the trials (resulting in about 360 trials) participants were presented with memory arrays of 3T in which the targets either formed a Kanizsa triangle (3T illusory object), appeared in a configuration of a triangle (3T proximity), or appeared in random positions (3T random). The probability of the 3T illusory object and the 3T proximity conditions was ninth each, resulting in about 60 trials for each condition, and the 3T random condition appeared in about 240 trials. About the remaining third of the trials were 3T3D trials in which the targets either formed a Kanizsa triangle (3T3D illusory object), appeared in a configuration of a triangle (3T3D proximity), or appeared in random positions (3T3D random). The probability for each of these three filtering conditions was ninth, resulting in about 60 trials for each of the 3T3D conditions. All six conditions were presented in nine intermixed blocks of 60 trials each, with a total of 540 trials. Ten practice trials were presented before the experiment. Participants were told that the targets could form a Kanizsa triangle, were shown an example of a Kanizsa triangle, and were told that in any case they should concentrate on remembering the orientations of the targets and ignore the distractors, independently of how the targets appeared (see Fig. 4a).

Visual working memory capacity estimates: change-detection task

Participants performed the change-detection task as in Experiment 1.

Results and discussion

Filtering change-detection task

Two-way repeated measures ANOVA with trial-type (3T, 3T3D) and grouping (illusory object, proximity, random) on accuracy rates as a dependent variable showed a main effect of trial-type [$F(1, 23) = 43.81$, MSE 0.00440, $p < 0.001$, $\eta_p^2 = 0.65$] and grouping [$F(2, 46) = 33.81$, MSE 0.00846, $p < 0.001$, $\eta_p^2 = 0.59$]. Importantly, there was a trial-type × grouping interaction [$F(2, 46) = 6.79$, MSE 0.00419, $p = 0.002$, $\eta_p^2 = 0.59$; see Fig. 4b]. Planned comparisons corrected to FDR *p* value of 0.025 (Benjamini & Hochberg, 1995) showed that filtering performance in the 3T3D illusory object condition (*M* 0.82, SD 0.13) was higher than filtering performance in the 3T3D proximity condition [*M* 0.65, SD 0.08; $F(1, 23) = 40.09$, MSE 0.0090, $p < 0.001$, $\eta_p^2 = 0.63$], replicating the results from Experiment 3, and further indicating that an illusory object cue compatible with the features of the Kanizsa triangle was able to boost filtering performance beyond the proximity cue. Filtering performance in the 3T3D proximity condition (*M* 0.65, SD 0.08) was now similar to filtering performance in the 3T3D random condition (*M* 0.65, SD 0.07; $F < 1$). This result is not consistent with Experiment 3 in which performance in the 3T3D proximity condition was better than performance in the 3T3D random condition. When directly comparing Experiment 3 and 4, it seems that although the 3T3D random condition is identical between the experiments, performance in Experiment 4 (*M* 0.65, SD 0.07) is better than performance in Experiment 3 (*M* 0.60, SD 0.06), a difference that was only marginally significant [$t(46) = -2.30$, $p = 0.0256$], while when comparing performance in the 3T3D proximity condition, it remained similar when comparing Experiment 3 (*M* 0.64, SD 0.07) and Experiment 4 [*M* 0.65, SD 0.08; $t(46) = -0.43$, $p > 0.1$]. Thus, perhaps due to some contextual effect, performance in the random condition improved in Experiment 4.

In the current experiment the grouping cues were applied also on the 3T conditions (only targets), in addition to the 3T3D conditions (that included distractors). This factorial design allowed a proper estimation of the extent to which the grouping cues improve filtering performance, by directly comparing the 3T grouped conditions to the 3T3D grouped conditions, both applying the same grouping principle. Accuracy in the 3T illusory object condition (*M* 0.84, SD 0.17) was similar to accuracy in the 3T3D illusory object condition (*M* 0.82, SD 0.13; $F < 1$), indicating that forming an illusory object improved filtering performance to the highest extent, such that the distractors were completely excluded from entering VWM. This further indicates that the finding from Experiment 3, in which performance in the 3T3D illusory object condition was higher than performance in the 3T condition was because we compared grouped targets (in the 3T3D condition) with ungroup targets (in the 3T condition). In addition, performance in the 3T proximity condition (*M* 0.76, SD 0.10) was higher than filtering performance in the 3T3D proximity condition [*M* 0.65, SD 0.08; $F(1, 23) = 31.80$, MSE 0.0046, $p < 0.001$, $\eta_p^2 = 0.58$], indicating that the proximity cue allowed for distractors to be processed to some extent. The findings from the present experiment demonstrate that, similar to Experiment 3, an illusory object cue applied on the targets was able to improve filtering performance to the highest extent, such that the distractors were completely filtered out from entering VWM, possibly due to better tagging of the grouped targets.

Experiment 5

The goal of Experiment 5 was to investigate whether an illusory object grouping cue applied on the distractors can affect tagging of the items as irrelevant and improve filtering performance beyond the proximity cue when using a task that was compatible with the formation of the Kanizsa triangle, possibly by helping the filtering mechanism to better reject distractors as a group. Namely, participants performed a change-detection task similar to the one in Experiment 3. However, this time the circles with a rectangle opening served as targets and the circles with a triangle opening served as distractors. In the filtering condition the distractors either formed a Kanizsa triangle (illusory object), appeared in a triangle-like configuration (proximity), or appeared at random positions (random), which did not encourage grouping of the distractors (see Fig. 5a).

Method

Participants

Twenty-four students from Tel Aviv University (19 females, *M* 22.5 years, SD 1.96) participated in the experiment. One subject was excluded from analysis due to below chance accuracy rates in the change-detection task.

Apparatus

The same apparatus was used as in Experiment 1.

Stimuli and procedure

Filtering change-detection task

Participants performed a change-detection task similar to the one in Experiment 3 except for the following. Participants were asked to remember the circles with a rectangle opening and ignore the circles with a triangle opening. To group the distractors, in the filtering condition the distractors either formed a Kanizsa triangle (3T3D illusory object),

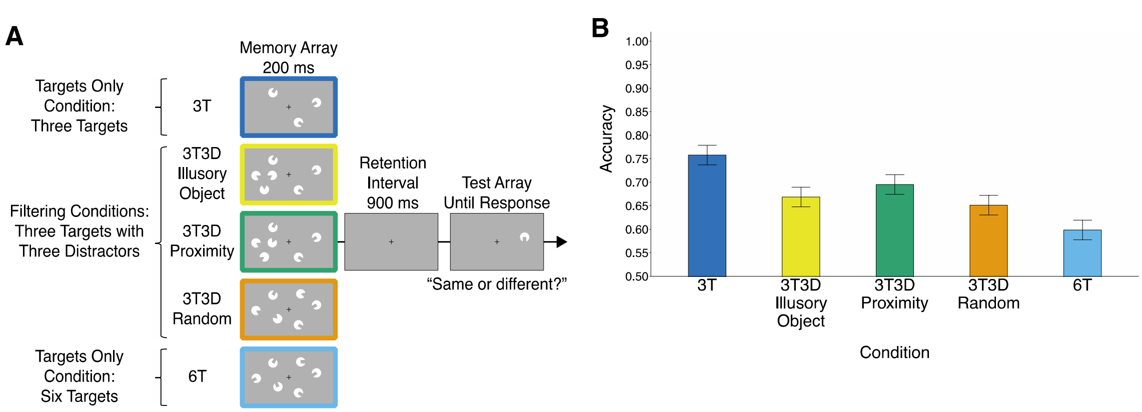

Fig. 5 **a** Example for a targets-only (i.e., three targets or six targets) and filtering trails (i.e., three targets along with three distractors) in Experiment 5. Participants were asked to remember the orientations of the circles with a rectangle opening and ignore the circles with a triangle opening. To group the distractors in the filtering conditions, the distractors either formed a Kanizsa triangle (grouping by illusory object), appeared in a configuration of a triangle (grouping by proximity), or appeared in random positions (no-grouping). **b** Results from Experiment 5. Accuracy as a function of condition. Error bars represent 95% confidence intervals according to Loftus and Masson (1994)

appeared in a triangle-like configuration (3T3D proximity), or appeared at random positions (3T3D random). Participants were told that the distractors could form a Kanizsa triangle, were shown an example of a Kanizsa triangle, and were told that in any case they should concentrate on remembering the orientations of the targets and ignore the distractors, independently of how the distractors appeared (see Fig. 5a). The probabilities for each of the conditions were the same as in Experiment 3.

Visual working memory capacity estimates: change-detection task

Participants performed the change-detection task as in Experiment 1.

Results and discussion

Filtering change-detection task

Repeated measures ANOVA was conducted as in Experiment 1. The ANOVA showed a main effect of condition [$F(4, 92) = 33.48$, MSE 0.00246, $p < 0.001$, $\eta_p^2 = 0.59$; see Fig. 5b]. Planned comparisons corrected to FDR *p* value of 0.025 (Benjamini & Hochberg, 1995) showed that accuracy in the 3T3D illusory object condition (*M* 0.66, SD 0.07) was lower than accuracy in the 3T3D proximity condition (*M* 0.69, SD 0.07), a difference that was not significant [$F(1, 23) = 3.44$, MSE 0.002476, $p = 0.07$, $\eta_p^2 = 0.13$]. In addition, accuracy in the 3T3D illusory object condition (*M* 0.66, SD 0.07) was similar to accuracy in the 3T3D random condition [*M* 0.65, SD 0.07; $F(1, 23) = 1.22$, MSE 0.002905, $p = 0.28$, $\eta_p^2 = 0.05$]. These results indicate that when the task was compatible with the Kanizsa triangle, an illusory object cue applied on the distractors was not able to improve filtering performance at all.

In addition, accuracy in the 3T3D proximity condition (*M* 0.69, SD 0.07) was higher than accuracy in the 3T3D random condition [*M* 0.65, SD 0.07; $F(1, 23) = 8.90$, MSE 0.002594, $p = 0.006$, $\eta_p^2 = 0.27$]. This result suggests that a proximity grouping cue alone applied on the distractors was able to improve filtering performance, replicating the results from Experiment 2. Accuracy in the 3T condition (*M* 0.75, SD 0.06) was higher than accuracy in the 3T3D proximity condition [*M* 0.69, SD 0.07; $F(1, 23) = 17.00$, MSE 0.002776, $p = 0.004$, $\eta_p^2 = 0.42$], indicating that while a proximity grouping cue applied on the distractors improved filtering performance, the distractors were processed to some extent, replicating the results of Experiment 2.

The results of the current experiment suggest that grouping the irrelevant information by proximity can enhance the rejection of the grouped distractors from entering VWM, possibly by enhancing the separation process between the relevant and the irrelevant items that was presumably carried out by better tagging of the irrelevant items as distractors. It is noteworthy that the potent Gestalt illusory object cue was not able to improve filtering performance relative to the random condition. Given its pre-attentive nature (e.g., Kimchi et al., 2007), and our previous finding in which this condition was able to improve filtering ability even beyond a proximity condition (Experiment 3), it is unlikely that participants did not perceive the Kanizsa triangle. Instead, we argue that in the current experiment, its power as a grouping cue that facilitates processing resulting from the cue and task compatibility was a disadvantage when processing the distractors. Presumably, the distractors were (sometimes) fully processed instead of being blocked once tagged as distractors.

Across experiments analysis

We sought to test whether grouping the targets or the distractors provides greater improvement in filtering performance. To this end, we applied two across experiments analysis, one for each task (i.e., color task and orientation task), with Experiment as a between-subject variable.

Across Experiment 1 and Experiment 2 analysis

A repeated measures two-way ANOVA with experiment (Experiment 1, Experiment 2) as a between-subjects independent variable and condition (3T, 3T3D illusory object, 3T3D proximity, 3T3D random, 6T) as a within-subjects independent variable on mean accuracy rates as a dependent variable revealed a main effect for condition [$F(4, 184) = 111.374$, MSE 0.0022, $p < 0.01$, $\eta_p^2 = 0.70$]. There was no main effect for experiment ($F < 1$). Interestingly, there was no experiment × condition interaction ($F < 1$; see Fig S2). These findings indicate that when the task was not compatible with the grouping cues, grouping the targets or the distractors results in the same improvement of filtering performance.

Across Experiment 3 and Experiment 5 analysis

A repeated measures two-way ANOVA with experiment (Experiment 3, Experiment 5) as a between-subjects independent variable and condition (3T, 3T3D illusory object, 3T3D proximity, 3T3D random, 6T) as a within-subjects independent variable on mean accuracy rate as a dependent variable revealed a main effect for condition [$F(4, 184) = 60.334$, MSE 0.0030, $p < 0.01$, $\eta_p^2 = 0.56$]. There was no main effect for experiment ($F < 1$). This time, the experiment × condition interaction was significant [$F(4, 184) = 15.897$, MSE 0.0030, $p < 0.01$, $\eta_p^2 = 0.25$; see Fig S3].

Planned comparisons corrected to p value of 0.025 showed that grouping the targets or the distractors by proximity resulted in the same magnitude of improvement in filtering performance relative to filtering performance in the random condition ($F < 1$), replicating the same trend from Experiment 1 vs. 2. However, grouping the targets by forming an illusory object resulted in a higher filtering performance (relative to filtering performance in the proximity cue) than when the distractors were grouped [$F(1, 46) = 36.95$, MSE 0.003924, $p < 0.001$, $\eta_p^2 = 0.44$]. This indicates that grouping the targets improved filtering performance more than grouping the distractors, only when the grouping cue was compatible with the task.

General discussion

The purpose of the current study was to manipulate the tagging process using perceptual grouping cues to examine if and when manipulating the tagging difficulty can affect filtering performance in VWM. Previous studies (e.g., Gao et al., 2016; Peterson & Berryhill, 2013) have shown that Gestalt grouping cues can improve general VWM performance in a situation in which all items are relevant. To the best of our knowledge, the current study is the first to show that Gestalt grouping cues can also improve VWM performance when both relevant and irrelevant items are present.

In five experiments, participants performed a change-detection task that included trials with only targets and trials with targets along with distractors. We applied two Gestalt grouping cues on the targets (Experiment 1, and Experiments 3–4) or on the distractors (Experiment 2 and Experiment 5) to vary the grouping level thereby manipulating the tagging difficulty, and two types of tasks (color task: Experiments 1–2; orientation task: Experiments 3–5) that further emphasized the Gestalt grouping principles.

The results showed that indeed, perceptual grouping can improve filtering performance in VWM. The proximity cue improved filtering performance relative to a non-grouping filtering condition when the targets or the distractors were grouped, and when the relevant task dimension was color or orientation. This pattern of results was different in Experiment 4, possibly due to an increase in performance in the filtering non-grouping condition (see Results and discussion section in Experiment 4 for further details).

While the illusory object grouping cue is considered a very strong Gestalt cue (e.g., Kimchi et al., 2007), this was not always reflected in its ability to improve the filtering performance. This grouping cue affected filtering performance based on the compatibility of the task with the cue. When the task was incompatible with the illusory object cue, such that the stimuli included different colors and the task required to remember the colors, an illusory object cue on the targets or on the distractors did not further improve filtering performance relative to the proximity cue. Moreover, when the task was compatible with the illusory object cue, such that the stimuli did not include colors and the task required to remember the orientations, an illusory object cue on the distractors resulted in similar filtering performance relative to filtering performance observed in the non-grouping condition. Only an illusory object grouping cue on the targets that was compatible with the task was able to improve filtering performance beyond the proximity cue.

The across experimental analysis suggested that when the task-relevant dimension is color, grouping the targets or the distractors results in the same improvement of filtering performance. Furthermore, when the relevant dimension is orientation, grouping the targets results in a larger improvement of filtering performance than when the distractors are grouped.

We suggest that Gestalt grouping cues used in the current study, which are known to enhance perceptual processing (Wagemans et al., 2012), affected VWM filtering performance through a tagging process that classifies items as relevant or irrelevant. This tagging process occurs as part of filtering out the irrelevant information from entering VWM and selecting only the relevant information. We suggest that in order for the filtering mechanism to be able to reject the distractors and enable the targets to be encoded into VWM, the filtering mechanism should first identify what is the relevant and what is the irrelevant information. For this differentiation process to occur, the system should process all the information to some extent until it can tag pieces of information as relevant, such that this information should be selected for further processing, or as irrelevant such that the information should not be selected for further processing. We propose that the grouping cues facilitated the tagging of the grouped items, thereby boosting the differentiation between what is the relevant and what is the irrelevant information, resulting in better filtering of irrelevant items from entering VWM (i.e., better filtering performance). Note that evaluating all the incoming information might result in processing the irrelevant information as well, which could lead do their full processing. When grouping was applied on the distractors and the task was compatible with the grouping cue (i.e., both relayed on orientation), The grouping cue did not aid the filtering mechanism. We suggest that in this situation, the tagging mechanism failed, because the illusory object cue strongly enhanced the distractor processing, such that the initial process of evaluating incoming items led (sometimes) to full processing of the grouped items.

The findings concerning the illusory object cue are in line with previous studies demonstrating that grouping cues forming a perceptual object, for example, using grouping by an illusory object, capture attention in a stimulus-driven manner (Kimchi et al., 2007, 2016), and thus support the idea according to which the deployment of attention depends on the "strength of objecthood" (Kimchi et al., 2016). Furthermore, the findings concerning the different influences of the proximity and illusory object grouping cues corroborate previous findings supporting the notion that not all grouping cues are equal (e.g., Kimchi & Razpurker-Apfeld, 2004).

Yet, another possible explanation for the superiority of the illusory object cue observed in some of the experiments in the present study (i.e., Experiment 3 and Experiment 4) might not be related to the tagging process per-se. Namely, it might be that in the illusory object conditions the targets were chunked such that participants encoded only one item (i.e., the Kanizsa triangle) instead of separately encoding the items that composed the Kanizsa triangle. Since only one (intergraded) item was encoded, this strategy resulted in high performance relative to the targets that were grouped by proximity and thereby were not perceived as one item. This possibility explains the boost in filtering performance by focusing on target related processes, as grouping in this case was applied on the targets. However, if this were the case, we should have expected performance in the 3T3D illusory object condition to reflect the encoding of just one item, which usually approaches ceiling level (e.g., Allon, Balaban, & Luria, 2014; Luck & Vogel, 1997; Vogel et al., 2001). Instead, performance in this condition was not particularly high (*M* 0.82, SD 0.13; Experiment 4), implying that participants were not representing just one item.

The results from Experiment 3 and Experiment 4 suggest that the estimation of the difference between the filtering and non-filtering conditions in previous studies (e.g., Astle et al., 2014; Fukuda & Vogel, 2009, Experiment 3; Lee et al., 2010; Vogel et al., 2005, Experiment 2) might have been inaccurate. The reason is that in these studies a target item (e.g., color) was allowed to repeat in the memory array, thus enabling participants to group the repeated stimuli by similarity, which is known to affect VWM performance (Gao et al., 2011; Lin & Luck, 2009; Peterson & Berryhill, 2013; Peterson et al., 2015; Quinlan & Cohen, 2012; Shen, Yu, Xu, & Gao, 2013). The current findings indicate that filtering ability and perceptual grouping interact, and that comparing filtering conditions to non-filtering conditions in a situation in which grouping cues are applied only on one of these conditions can result in an underestimation of the difference in performance between the filtering and non-filtering conditions. Therefore, it is important for future studies to separate the filtering and grouping mechanisms if needed to get a clean estimation of performance.

To summarize, research on filtering irrelevant information has mainly centered on studying the various circumstances under which individuals demonstrate poor filtering ability, resulting in a decrement in task performance in either response speed, accuracy, or both (e.g., Anderson, Laurent, & Yantis, 2011; Eriksen & Eriksen, 1974; Folk, Leber, & Egeth, 2002, 2008; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994; MacLeod, 1991; Stroop, 1935; Theeuwes & Godijn, 2002; Yantis, 1996). Hence, it is important to understand which compensation mechanisms are available to overcome insufficient filtering of irrelevant information. The findings of the current study carry significance by specifying the conditions under which Gestalt grouping cues can serve as compensation mechanisms for improving filtering performance in VWM.

Data availability The datasets analyzed during the current study are available in the Open Science Framework repository, https://osf.io/c6ezs/.

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Compliance with ethical standards

Ethical approval Participants in all five experiments of the current study gave their informed consent after the procedures of a protocol approved by the Ethics Committee at Tel Aviv University. This study was supported by the Israel Science Foundation Grant number 1696-13 awarded to Roy Luria.

Conflict of interest The authors declare that they have no conflict of interest.

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