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Proactive suppression is evident even if the probe-recognition assumption is not evident: complementary relationship between proactive and reactive suppression

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ABSTRACT

In capture-probe paradigms, probes presented in salient distractors are less frequently recognized than probes in non-salient distractors. This probe-recognition frequency effect could be due to attention going less frequently towards the salient distractors (proactive suppression) and/or dwelling more shortly on the salient distractors (reactive suppression). However, the probe-recognition frequency effect was considered as evidence supporting only proactive suppression based on the probe-recognition assumption where if attention is directed towards the probes, their correct identification should occur irrespective of whether attention disengages quickly or slowly. The present study revealed less accurate probe-recognition in the salient than non-salient distractors, inconsistent with the assumption and consistent with reactive suppression. To examine proactive suppression despite the assumption invalid, we measured how frequently the probes were attended by asking participants to always attempt the probe tests wherever they saw them, irrespective of whether they were able to recognize the attended probes or not. This probe-detection frequency showed less frequent attention towards the salient than non-salient distractors. The present findings suggest that proactive suppression is evident even if the probe-recognition assumption is not evident, and proactive and reactive suppression operate in concert to reduce the processing of distracting information.

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Attentional capture; proactive suppression; reactive suppression; dual mechanisms of control

Proactive suppression is evident even if the probe-recognition assumption is not evident

Selective attention operates not only to enhance the processing of task-relevant information, but also to suppress the processing of tasks-irrelevant information. For instance, a basketball player must effectively ignore distracting information, such as spectators behind the backboard, to maintain focus on the basket while taking a shot. Recent studies using a capture-probe paradigm propose that attention is suppressed proactively in perception. For example, the player proactively ignores the spectators, so that attention is never towards them (Addleman & Störmer, 2022; Chang & Egeth, 2019, 2021; Gao & Theeuwes, 2020; Gaspelin et al., 2015; Kim & Cho, in press; Kong et al., 2020; Wang & Theeuwes, 2020; Won et al., 2019; Zhang et al., 2020). However, it has been consistently questioned that evidence of the proactive suppression obtained in the capture-probe paradigm may reflect reactive suppression in the attentive stage. For example, although the spectators capture the player's attention, the player can rapidly disengage attention from them to focus on the basket (Geng & Duarte, 2021; Moher & Egeth, 2012).

The capture-probe paradigm consists of frequent search-task trials and infrequent probe-task trials, which are presented in random order. On the search-task trials, a diamond, a circle, a hexagon, and a square are presented. Participants search for a specific shape (e.g., circle) and report whether a dot is on the left or right of the target. On some search-task trials, one of the nontarget shapes has a unique colour, which is a colour singleton distractor. On the probe-task trials, the search items are briefly presented, and each shape contains a letter. Participants are asked to recall as many letters (probe stimuli) as possible without indicating the locations of the letters. Critically, it has been found that participants recall letters presented on the colour singleton distractor less frequently than letters presented on the nonsingleton distractors (a baseline), *a probe-recognition frequency effect* (or a probe suppression effect, Chang et al., 2023; Gaspelin et al., 2015; Won et al., 2019). This effect led researchers to conclude that the singleton

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distractor is *proactively* suppressed so that attention is less frequently allocated to the colour singleton than nonsingleton distractors. However, it remains questionable whether the probe-recognition frequency effect reflects only proactive suppression.

Two mechanisms for attentional control have been proposed: proactive control for early selection and reactive control for late correction (Braver et al., 2007). Proactive suppression prevents initial attentional selection of distractors in the pre-attentive stage; therefore, attention is not allocated to the suppressed distractors (Forstinger et al., 2022; Gaspelin et al., 2015). In contrast, reactive suppression occurs after attention is allocated to distractors. Reactive suppression operates to correct the attentional allocation by rapidly disengaging attention from the distractors; that is, attention dwells very briefly (Geng, 2014; Geng & Duarte, 2021; Moher & Egeth, 2012; Theeuwes et al., 2000). The key difference of the mechanisms is whether attention is allocated to the suppressed distractors (reactive suppression) or not allocated (proactive suppression).

The reactive suppression mechanism also can lead to a probe-recognition frequency effect because probes in the singleton distractor could be attended more briefly (van Moorselaar & Slagter, 2020). Theories and models of attention suggest that sufficient attention to a stimulus is necessary for conscious recognition of it (Bundesen, 1990; Chun & Potter, 1995; Desimone & Duncan, 1995; Treisman & Gelade, 1980; Wolfe, 1994). Bundesen and Harms (1999) investigated the time course of single-stimulus identification. In their experiment, the exposure duration of a stimulus varied from 10 to 200 ms. Critically, the probability of recognizing the stimulus increased as the exposure duration increased (see Figure 1 for a typical function of stimulus recognition and exposure duration). This finding suggests that short attentional-dwell-time may deteriorate the identification of the attended probe in the probe task (Bundesen & Harms, 1999; Parasuraman et al., 1982; Shibuya & Bundesen, 1988). Therefore, if attention is more rapidly disengaged in the singleton than nonsingleton distractors, probes in the singleton distractors will be less accurately recognized than those in the nonsingleton distractors. As a result, probes in the singleton distractors will be less frequently reported than probes in the nonsingleton distractors, resulting in the probe-recognition frequency effect.

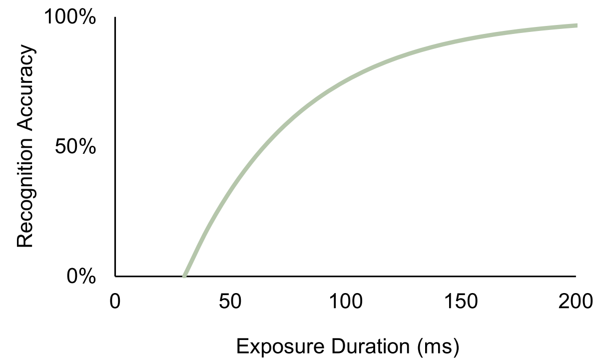

Figure 1. A typical pattern for recognition accuracy of a single stimulus as a function of exposure duration (Bundesen & Harms, 1999; Shibuya & Bundesen, 1988).

To rule out the possibility that recognition accuracy contributes to the probe-recognition frequency effect, previous research using the capture-probe paradigm was conducted under the assumption that the identification of probes should remain unaffected by how long attention dwells on the probes (e.g., Gaspelin et al., 2015). That is, the probes in both the singleton and nonsingleton distractors should be equally accurately identified even if reactive suppression occurs so that attention is disengaged more rapidly in the singleton than nonsingleton distractors. Thus, the probe-recognition frequency effect reflects how frequently probes are attended but not how long they are attended, such that it is evidence only for proactive suppression. However, the probe-recognition assumption contradicts the previous findings of the relationship between attention and recognition (Bundesen & Harms, 1999).

Present study

The purpose of the present study is both to assess the probe-recognition assumption and to investigate the proactive suppression account using a measurement which is independent of whether the probe-recognition assumption is valid or invalid.

Testing of probe-recognition assumption: Probe-recognition accuracy

The present study directly examined the probe-recognition assumption that *the probe-recognition accuracy* (correct response / total response) for each of the probe types (singleton distractors, nonsingleton distractors, targets) is not different. In the classic probe task, the probe-recognition accuracy for each probe type could not be estimated because participants recalled probes without indicating the locations of the probes (Kerzel & Renaud, 2023). For example, when participants inaccurately report the presence of a letter "E" which was not presented, it is not possible to determine whether participants inaccurately saw the E in the target location, the singleton distractor location, or the nonsingleton distractor locations. The capture-probe paradigm in the present study, therefore, was designed to record where participants attempted a probe test. This allowed for calculating the probe accuracy for each probe type and so directly examining the probe-recognition assumption.

Comparisons between probe-recognition frequency and probe-recognition accuracy

The process of simple detection, assessing the presence or absence of a probe regardless of its correct or incorrect recognition, demands minimal attentional resources (Lavie, 1995; Joseph et al., 1997). Detection is followed by recognition (Bundesen & Harms, 1999; Parasuraman et al., 1982). These findings suggest that the recognition stage involves reactive suppression, which occurs after attentional selection, rather than proactive suppression, which occurs before attentional selection. Moreover, the detection stage involves early attentional selection.

The probe-recognition frequency, which measures how many probes are correctly recognized, reflects both the detection and recognition stages because probe recognition fails when probes are not detected or when probes are detected but incorrectly recognized. Therefore, this measurement involves both proactive and reactive suppression mechanisms. On the other hand, the probe-recognition accuracy focuses solely on the recognition stage but not the detection stage, as it measures the proportion of recognized probes among those already detected (attended). Therefore, as detection demands minimal attentional resources (Lavie, 1995; Joseph et al., 1997) and recognition follows detection (Bundesen & Harms, 1999; Parasuraman et al., 1982), the probe-recognition accuracy primarily reflects reactive suppression rather than proactive suppression.

To interpret the traditionally measured probe-recognition frequency effect as an indicative of proactive suppression rather than reactive suppression, previous research utilizing the capture-probe paradigm (e.g., Gaspelin et al., 2015; Gaspelin & Luck, 2018; Won et al., 2019) assumed that the probe-recognition accuracy would be consistent across the target, singleton distractor, and nonsingleton distractor. If this assumption remains valid, there would be no discrepancy in the probe-recognition accuracy across different probe types. However, if the assumption proves invalid, their probe-recognition accuracy would differ. Particularly, if the assumption is found to be invalid due to reactive suppression (van Moorselaar & Slagter, 2020), the probe-recognition accuracy would be lower for the singleton than nonsingleton distractor because more rapid attentional disengagement for the singleton than nonsingleton distractor will result in poorer probe-recognition for the singleton than nonsingleton distractor (Bundesen & Harms, 1999; van Moorselaar & Slagter, 2020).

Testing of proactive suppression: Probe-detection frequency

Basically, the necessity of the probe-recognition assumption in the traditional capture-probe paradigm is attributed to the methodological limitation that the probe-recognition frequency measures only the probes attended and correctly recognized but not the probes attended and incorrectly recognized. We solved this limitation by measuring the detection of probe presence. Participants were instructed to always attempt a probe test wherever they attended them regardless of whether the probes were fully recognized or not. *This probe-detection frequency* includes the probes attended and correctly recognized and the probes attended and incorrectly recognized, such that the probe-recognition assumption is unnecessary.

Another advantage of the probe-detection frequency is that it can measure the attentional allocation more sensitively than the probe-recognition frequency (Joseph et al., 1997; Lavie, 1995). It has been found that while stimulus identification is substantially influenced by attentional resources (Bundesen & Harms, 1999; Shibuya & Bundesen, 1988), stimulus presence is easily noticed with minimum attentional resources (Joseph et al., 1997; Posner et al., 1980; Treisman & Gelade, 1980); for example, we sometimes experience being aware of things without recognition of them (Lavie, 1995). Therefore, the probe-recognition frequency, encompassing both detection and recognition, would miss some attended probes when the attended probes were detected but not correctly recognized. In contrast, the probe-detection frequency has the capacity to encompass such instances. If proactive suppression occurs for the singleton distractors, probe tests will be less frequently attempted at the singleton than nonsingleton distractors.

Method

Participants

Forty-two participants with normal or corrected-to-normal visual acuity and colour vision were recruited with a payment of KRW 11,000 (about $9). It was assumed that the sample size was sufficient for detecting the probe-recognition frequency effect given that G-power analysis with a power of .95, an alpha of .05, and an effect size of 1.25 (Won et al., 2019) suggested a minimum sample size of 12 for detecting different performance in the probe task.

Apparatus

Stimuli were presented on a 17-inch CRT monitor. The viewing distance was approximately 60 cm but was not constrained. The experiment was programmed and administered using MATLAB R2019a and Psychophysics Toolbox Version 3 software. Responses were recorded using a standard 101-key keyboard. The experiment was conducted individually in a dimly lit, sound-attenuated room.

Stimuli

The search display contained one hexagon (2.2° in width and height), one square (2.0° × 2.0°), one circle (2.2° in diameter), and one diamond (2.6° × 2.6°; see Figure 2). Each shape contained a black dot (0.24°) located on either left or right. The four shapes were arranged in a diamond pattern (4.9° in width and height). The probe display had the same search stimuli, but each shape contained a line. The orientations of the four lines were different (a vertical line, a 45° tilted line, a horizontal line, and a 135° tilted line; see Figure 2). Then, each shape was masked by a circle (1.8° in diameter). In the probe response display, each shape had four white lines (1.6° for each line). A centre fixation (0.3° × 0.3°) was always visible in the displays for the search and probe tasks.

Design and procedure

In the present experiment, there were search-task trials (70% of the total trials) and probe-task trials (30% of the total trials), which were presented in a random order (Figure 2).

On the search-task trials (70% of the total trials), a blank display appeared for 500 ms, followed by a fixation display of 1,000 ms. Then, a search display was presented until a response was made. In the search display, participants were instructed to search for a particular shape (the target was consistent for each participant; a diamond for half of the participants and a circle for the other participants) and to report whether the dot in the target shape was on the left or right by pressing the "Z" or "X" key of the keyboard with either their left index or middle finger, respectively. On 50% of the search-task trials, all shapes were the same colour (red for half participants and green for the other half). On the remaining search-task trials, one of distractors was a different colour (either green or red). Therefore, this colour singleton was always a distractor. If response times were longer than 2,000 ms, visual feedback of "반응이 느립니다" ("slow response" in Korean) was presented immediately after the response was given. If an incorrect response was made, visual feedback of "틀렸습니다" ("incorrect" in Korean) was presented immediately after the response.

Each probe-task trial (30% of the total trials) consisted of a 500-ms blank display, a 1,000-ms fixation display, a 150-ms probe display, a 500-ms mask display, and a probe response display presented until a response, consecutively (see Figure 2). The probe display was the same as the search display except that a line was superimposed on each shape (see Figure 2). In the mask display, the lines disappeared, and the circle masks appeared to erase the iconic memory of the lines (Enns & Di Lollo, 1997; Jiang & Chun, 2001). Importantly, in the probe response display, it was emphasized to participants that they should respond to the probe lines at locations of the shapes they had attended even though attentional-dwell-time was insufficient to fully identify the probes by clicking the mouse with

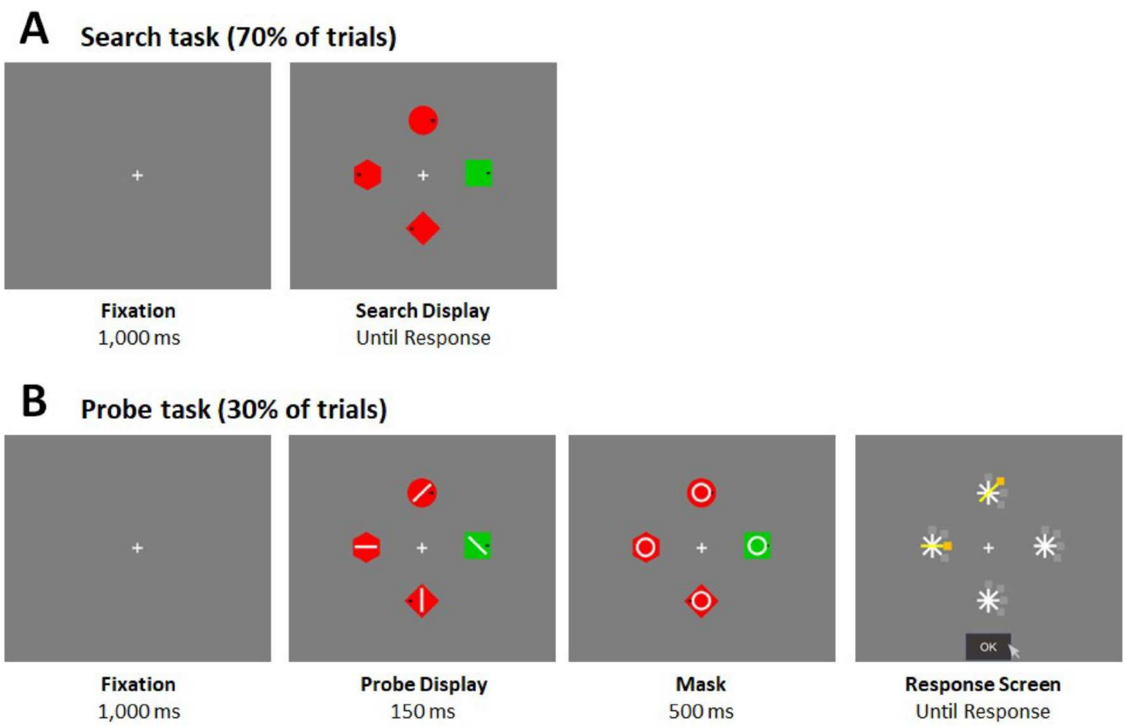

Figure 2. (a) An example of a search-task trial. Participants were tasked with locating a particular shape (e.g., diamond) and determining whether the dot within the target shape was on the left or right. In this example, the diamond is located at the bottom, and the dot within it is on the left. (b) An example of a probe-task trial. Each item contains a line (probe). Participants were asked to report the orientation of the lines (probes) they attended. Also, they were instructed to always attempt the probe test at the attended location, even if they were unsure about the exact identity of the attended probe. Furthermore, the experiment recorded where participants attempted the probe test, as seen in the response screen. As a result, both the recognition accuracy (the number of correct responses / the number of correct and incorrect responses) and the detection frequency (the number of correct and incorrect responses) can be obtained for each probe type (the target, the singleton distractor, the nonsingleton distractor).

the right hand. This would minimize a potential decision-making bias where participants are less likely to attempt a probe test in the singleton distractor (Kerzel & Renaud, 2023). Participants indicated the remembered line orientation (vertical, horizontal, diagonal right, diagonal left) of the selected stimulus by clicking on one of four lines that were shown at the location of the stimulus. Clicked lines turned yellow. After reporting all lines, they clicked an "OK" box (5.4° × 2.9°).

Previous research suggests that past experiences play an important role not only in attentional enhancement but also in attentional suppression (Awh et al., 2012; Gaspelin et al., 2015; Gaspelin & Luck, 2018; Kim & Beck, 2020; Theeuwes, 2019; Theeuwes & Failing, 2020; Vatterott & Vecera, 2012). For example, Gaspelin and Luck (2018) suggested that consistent exposure to a specific colour (e.g., red) as a salient distractor can lead the visual system to suppress attention to that colour. Consequently, substantial practice with a search task has been recommended or required for attentional suppression to occur in the previous studies (Gaspelin et al., 2015; Gaspelin & Luck, 2018; Vatterott & Vecera, 2012). Therefore, our participants engaged in two blocks of 48 trials practicing the search task and then proceeded to two additional blocks of 48 trials involving both the search and probe tasks, as in Gaspelin et al. (2015) and Gaspelin and Luck (2018) studies. The main experiment consisted of 8 blocks of 90 trials. Fifteen-second breaks were given between blocks.

Results

Search Task

Trials in which response time (RT) was shorter than 250 ms (0.01% of trials) or longer than 1,500 ms (1.13%) were excluded from the analyses. Furthermore, incorrect response trials were excluded (3.31%). RTs were not significantly different between singleton-present trials (Mean (M) = 679 ms, Standard

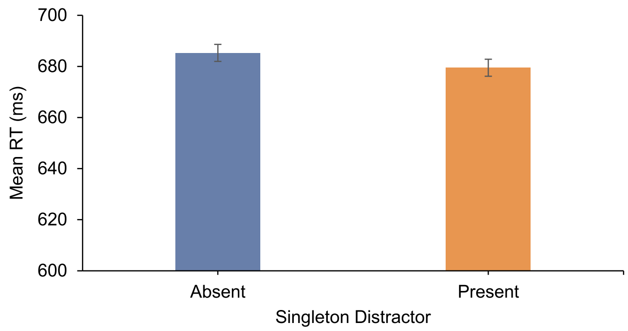

Figure 3. Response times in the search-task trials. Error bars indicate 95% confidence intervals (Loftus & Masson, 1994).

Deviation (SD) = 87 ms) and singleton-absent trials (M = 685 ms, SD = 91 ms), $t(41) = 1.71$, $p = .09$, $d = .26$ (see Figure 3); however, the direction of this numerical difference was consistent with the previous study (Gaspelin et al., 2015). Accuracy was not significantly different between singleton-present trials (M = 96.9%, SD = 2.6%) and singleton-absent trials (M = 96.4%, SD = 3.3%), $t(41) = 1.67$, $p = .103$, $d = .25$ (see Figure 4). The results indicate little distraction of the singleton distractor because the attend-to-me signal of the singleton distractors was inhibited (Bacon & Egeth, 1994; Gaspelin et al., 2017). Note that attentional suppression has not been sensitively measured in search speed (e.g., Bacon & Egeth, 1994; Gaspelin et al., 2017).

Probe Task

Participants reported an average of 1.85 lines per trial, 83.10% of which were correct. The number of reported probes was not significantly different between singleton-present trials ($M = 1.85$) and singleton-absent trials ($M = 1.86$), $t(41) = .56$, $p = .58$.

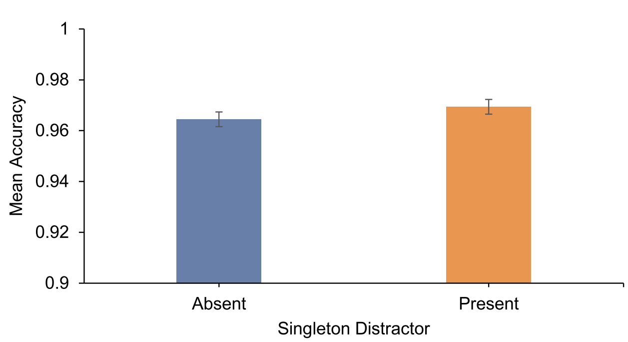

Figure 4. Accuracy in the search-task trials. Error bars indicate 95% confidence intervals (Loftus & Masson, 1994).

Probe-recognition frequency (traditional measurement). Before analyzing the probe-detection frequency and the probe-recognition accuracy, we confirmed that the probe-recognition frequency effect was replicated. Note that we report the ratio of the frequency to consider the different numbers of each probe type (e.g., one target, one singleton distractor, two nonsingleton distractors if the singleton distractor was presented).

A two-way analysis of variance (ANOVA) conducted on correct frequency with singleton presence (presence or absence) and probe type (targets or nonsingleton distractors) as within-subject factors revealed that probe-recognition frequency occurred more frequently for targets than nonsingleton distractors, $F(1, 41) = 11.16$, $p = .002$, $\eta_p^2 = .21$, indicating the facilitation of the targets (see Figure 5; Gaspelin et al., 2015). The probe-recognition frequency was higher for singleton presence than absence, $F(1, 41) = 4.23$, $p = .046$, $\eta_p^2 = .09$, replicating the previous study (Gaspelin et al., 2015). An interaction of singleton presence and probe type was not significant, $F(1, 41) = 2.02$, $p = .16$, $\eta_p^2 = .047$.

Correct responses were more frequent for target (M = 39.0%, SD = 13.8%) than nonsingleton distractors when no singleton distractor was present (M = 36.4%, SD = 13.9%), $t(41) = 2.54$, $p = .015$, $d = .39$. They were higher for target (M = 40.1%, SD = 13.9%) than nonsingleton distractors when the singleton distractor was present (M = 36.8%, SD = 13.8%), $t(41) = 3.43$, $p = .001$, $d = .53$. Critically, correct responses were less frequent for singleton (M = 32.2%, SD = 14.2%) than nonsingleton distractors when a singleton distractor was present (M = 36.8%, SD = 13.8%), $t(41) = 3.36$, $p = .002$, $d = .51$, indicating a probe-recognition frequency effect. This effect has traditionally been regarded as evidence for proactive suppression of the singleton distractor.

Probe-recognition accuracy (correct response frequency / total response frequency). In the probe-recognition frequency (traditional measurement), we successfully replicated the probe-recognition frequency effect, where probes at the singleton distractor location were reported less frequently than probes at the nonsingleton distractor location. However, for this effect to imply proactive suppression, it is necessary to assume that recognition accuracy is consistent regardless of whether a probe is presented at the target location, the singleton distractor location, or

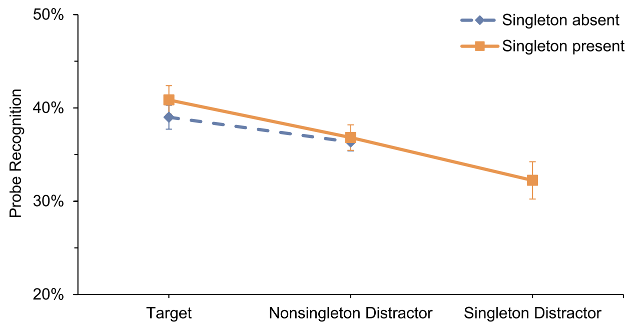

Figure 5. Proportion of probe-recognition frequency (the traditional measurement) in the probe-task trials. Error bars indicate 95% confidence intervals (Loftus & Masson, 1994).

the nonsingleton distractor location. If this assumption is invalid, it remains unclear whether the probe-recognition frequency effect indicates reduced attention toward probes at the singleton distractor location, poorer recognition of probes at that location, or both. Therefore, the present study was designed to monitor the locations where participants attempted a probe test (Figure 2), allowing us to investigate whether the recognition accuracy for probes at the target, singleton distractor, and nonsingleton distractor locations is equivalent or not. Below, the results of the probe-recognition accuracy analysis revealed that the assumption is indeed invalid.

A two-way ANOVA as a function of singleton presence (presence or absence) and probe type (targets or nonsingleton distractors) showed that the accuracy was not significantly different between a target and nonsingleton distractors, $F(1, 41) = 3.63$, $p = .064$, $\eta_p^2 = .08$, and between singleton present and absent, $F(1, 41) = .38$, $p = .54$, $\eta_p^2 = .009$ (see Figure 6). The interaction between the singleton presence and probe type was not significant, $F(1, 41) = .08$, $p = .77$, $\eta_p^2 = .002$.

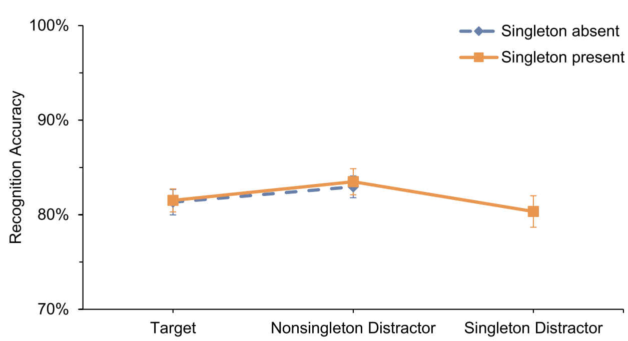

Figure 6. Recognition accuracy for the detected probes in the probe-task trials. Error bars indicate 95% confidence intervals (Loftus & Masson, 1994).

The probe-recognition accuracy did not differ significantly between the probes presented on the singleton distractor (M = 81.3%, SD = 13.8%) and those on the nonsingleton distractors (M = 82.9%, SD = 12.4%) in the absence of the singleton distractor, $t(41) = 1.50$, $p = .141$, $d = .23$. Similarly, when the singleton distractor was present, no significant difference was obtained in probe-recognition accuracy between probes on the singleton distractor (M = 81.5%, SD = 13.1%) and nonsingleton distractors (M = 83.5%, SD = 12.0%), $t(41) = 1.71$, $p = .095$, $d = .26$. Importantly, participants demonstrated lower accuracy in memorizing probes presented on the singleton distractor (M = 80.3%, SD = 13.7%) than those on the nonsingleton distractors (M = 83.5%, SD = 12.0%) when the singleton distractor was present, $t(41) = 3.26$, $p = .002$, $d = .50$, challenging the probe-recognition assumption. This finding aligns with the idea of previous research (van Moorselaar & Slagter, 2020) suggesting that the reduced recognition of probes at the singleton distractor location contributes, at least in part, to the probe-recognition frequency effect.

Probe-detection frequency. The finding that the probe-recognition assumption is invalid does not necessarily negate the possibility of proactive suppression for singleton distractors. In the present probe task, participants were instructed to engage in a probe test even if they did not fully recognize attended probes (simple detection). This simple detection measures both an attended and recognized probe and an attended but not recognized probe (Joseph et al., 1997; Lavie, 1995). By employing this method, we can explore attention allocation without relying on the probe-recognition assumption. The findings from the probe-detection frequency analysis below indicate that attention was indeed proactively suppressed for the singleton distractor.

A two-way ANOVA on probe-detection frequency as a function of singleton presence (presence or absence) and probe type (targets or nonsingleton distractors) revealed that the probe-detection frequency was higher for the target than the nonsingleton distractors, $F(1, 41) = 25.43$, $p < .001$, $\eta_p^2 = .38$, indicating that the target was selected more frequently than the nonsingleton distractors (see Figure 7). The detection frequency was higher for the singleton presence than absence, $F(1, 41) = 5.46$, $p = .024$, $\eta_p^2 = .117$. An interaction between singleton presence and probe

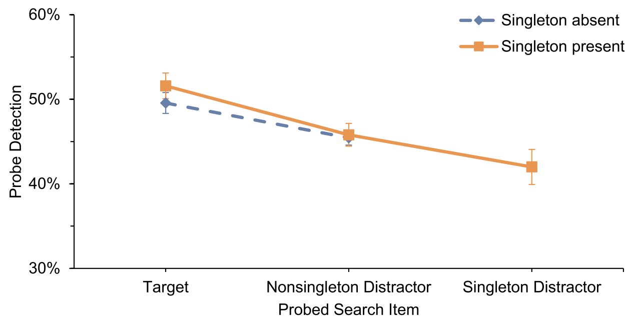

Figure 7. Proportion of the probe detection frequency in the probe-task trials. Error bars indicate 95% confidence intervals (Loftus & Masson, 1994).

type was not significant, $F(1, 41) = 3.56$, $p = .066$, $\eta_p^2 = .08$.

Participants showed a higher frequency of attempting the probe test at the target location (M = 49.6%, SD = 20.0%) than the nonsingleton distractor location (M = 45.4%, SD = 20.0%) in the absence of the singleton distractor, $t(41) = 4.09$, $p < .001$, $d = .63$. Also, in the presence of the singleton distractor, they attempted the probe test at the target location (M = 51.6%, SD = 20.1%) more frequently than the nonsingleton distractor location (M = 45.8%, SD = 20.2%), $t(41) = 5.07$, $p < .001$, $d = .78$. Importantly, participants attempted the probe test at the singleton distractor location (M = 42.0%, SD = 21.5%) less frequently than the nonsingleton distractor location (M = 45.8%, SD = 20.3%) in the presence of the singleton distractor, $t(41) = 2.59$, $p = .013$, $d = .39$, indicating proactive suppression for the singleton distractors.

Taken together, the findings of the probe-recognition frequency, probe-recognition accuracy, and probe-detection frequency analyses suggest that the traditional measurement of the probe-recognition frequency effect was due both to less frequent attention towards probes and to poorer recognition of probes at the singleton than nonsingleton distractor location.

Correlation analyses. The finding that attentional selection (probe-detection frequency) and recognition (probe-recognition accuracy) contributed to the probe-recognition frequency effect (traditional measurement) suggests that there would be correlations between the probe-recognition frequency (Figure 5) and both probe-recognition accuracy (Figure 6) and probe-detection frequency (Figure 7). Positive correlations were consistently observed in all six tests conducted, further suggesting that accurately reporting probes in the traditional measurement requires both early attentional selection towards probes and successful recognition of probes. Note that the critical p value for the correlation tests was adjusted to .0083 (.05/6) using the Bonferroni correction.

A positive correlation was found for the difference of the target and nonsingleton distractors between in the probe-recognition frequency and the probe-detection frequency when the singleton distractor was present, $r(40) = .87$, $p < .001$ (Figure 8(a)). A positive correlation was found for the difference of the target and nonsingleton distractor between in the probe-recognition frequency and the probe-recognition accuracy when the singleton distractor was present, $r(40) = .47$, $p = .002$ (Figure 8(b)). A positive correlation was found for the difference of the singleton and nonsingleton distractor between in the probe-recognition frequency and the probe-detection frequency, $r(40) = .95$, $p < .001$ (Figure 8(c)). A positive correlation was found for the difference of the singleton and nonsingleton distractors between the probe-recognition frequency and the probe-recognition accuracy, $r(40) = .43$, $p = .005$ (Figure 8(d)). A positive correlation was found for the difference of the target and nonsingleton distractors between in the probe-recognition frequency and the probe-detection frequency when the singleton distractor was absent, $r(40) = .82$, $p < .001$ (Figure 8(e)). A positive correlation was found for the difference of the target and nonsingleton distractors between in the probe-recognition frequency and the probe-recognition accuracy when the singleton distractor was absent, $r(40) = .57$, $p < .001$ (Figure 8(f)). Note that accuracy-based measures are suggested to be suitable to individual differences investigations in cognitive tasks while RT-based measures may not be suitable (Draheim et al., 2021).

Discussion

Probe-recognition frequency (traditional measurement)

While we successfully replicated the probe-recognition frequency effect, indicating a lower reporting frequency for probes presented in singleton distractors than those in nonsingleton distractors, its interpretation as evidence for proactive suppression

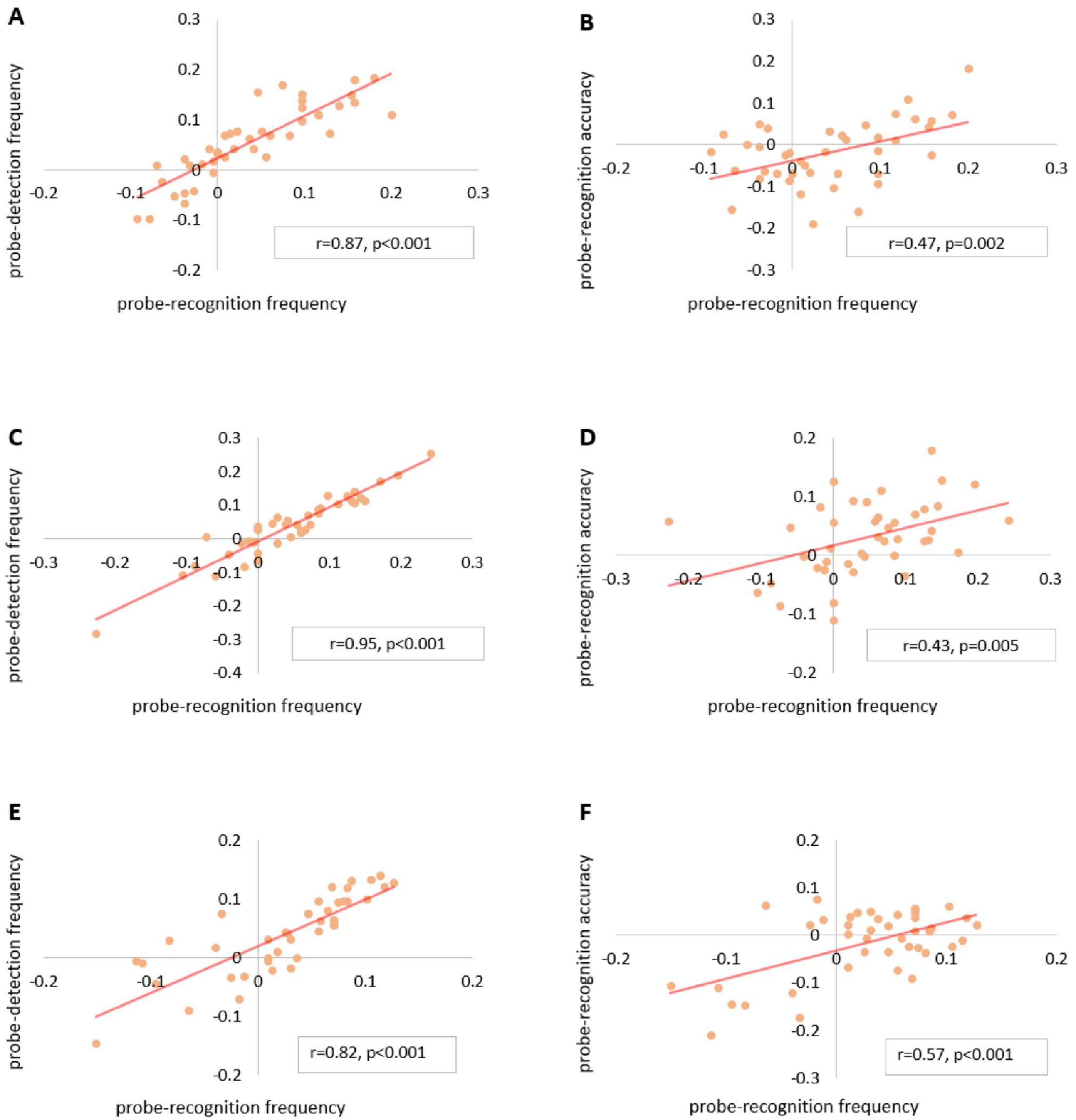

Figure 8. Panel (a) illustrates a correlation between the probe-recognition frequency and the probe-detection frequency for the difference between the target and nonsingleton distractor when the singleton distractor was present. Panel (b) illustrates a correlation between the probe-recognition frequency and the probe-recognition accuracy for the difference between the target and nonsingleton distractor when the singleton distractor was present. Panel (c) illustrates a correlation between the probe-recognition frequency and the probe-detection frequency for the difference between the singleton and nonsingleton distractor. Panel (d) illustrates a correlation between the probe-recognition frequency and the probe-recognition accuracy for the difference between the singleton and nonsingleton distractor. Panel (e) illustrates a correlation between the probe-recognition frequency and the probe-detection frequency for the difference between the target and nonsingleton distractor when the singleton distractor was absent. Panel (f) illustrates a correlation between the probe-recognition frequency and the probe-recognition accuracy for the difference between the target and nonsingleton distractor when the singleton distractor was absent.

of singleton distractors may be challenged (van Moorselaar & Slagter, 2020). There is a possibility that the observed effect may stem from impaired recognition of probes at the singleton distractor location compared to the nonsingleton distractor location (Figure 1; Bundesen & Harms, 1999; Shibuya & Bundesen, 1988). While previous studies assumed the absence of such a possibility (Gaspelin et al., 2015; Won et al., 2019), they were unable to validate this assumption because participants reported probes without specifying their presentation location.

Thus, the present study evaluated the probe-recognition assumption by assessing the probe-recognition accuracy for each probe type. Additionally, proactive suppression of singleton distractors was explored through the measurement of the simple probe detection. The use of simple detection provided a means to evaluate proactive suppression without relying on the probe-recognition assumption.

Probe-recognition accuracy

The present probe task recorded the locations where participants conducted a probe test (Figure 2). This allowed for the computation of probe-recognition accuracy for each type of probes, enabling an in-depth examination of the probe-recognition assumption. Importantly, the results of the probe-recognition accuracy analysis indicated that the recognition accuracy for probes in the singleton distractor was lower than those in the nonsingleton distractor, which is inconsistent with the probe-recognition assumption. That is, the probe-recognition frequency effect (traditional measurement) obtained in the present study was at least in part due to the lower recognition-accuracy in the singleton than nonsingleton distractors (van Moorselaar & Slagter, 2020). For example, sometimes participants did not fully identify attended probes, and such cases occurred more likely in the singleton than nonsingleton distractors. Furthermore, lower recognition accuracy of probes at the singleton than nonsingleton distractor suggests reactive suppression rather than proactive suppression, as the probe-recognition accuracy measured the proportion of recognized probes among those that were already attended to.

This idea was further confirmed in the correlation tests. The magnitudes of the probe-recognition frequency effect and the probe-recognition accuracy effect covaried across participants, further confirming that because participants identified probes less accurately for the singleton than nonsingleton distractors, they reported correct probes less frequently for the singleton than nonsingleton distractors.

Probe-detection frequency

The finding that the probe-recognition assumption is not valid does not conclusively dismiss the possibility of proactive suppression for the singleton distractor. It remains plausible that the observed probe-recognition frequency effect, which is less frequent reporting of probes at the singleton than nonsingleton distractors, may stem from both poorer recognition of and less frequent attention towards probes at the singleton location than the nonsingleton distractor location.

To independently investigate proactive suppression without relying on the probe-recognition assumption, participants were instructed to attempt the probe test at every attended location, regardless of whether they were certain about the exact identity of the attended probe. Simple detection, requiring minimal attentional resources compared to identification (Lavie, 1995; Joseph et al., 1997; Posner et al., 1980; Treisman & Gelade, 1980), reflects attention towards probes regardless of their recognition status. Consequently, probe-detection frequency, which measures the number of simple detection, can evaluate proactive suppression even in situations where the probe-recognition assumption is not valid.

Importantly, the results of the probe-detection frequency analysis indicated that participants attempted a probe test less frequently at the singleton than nonsingleton distractors. This finding implies that probes were less frequently detected at the singleton than nonsingleton distractor location. This simple detection, signifying awareness of stimulus presence regardless of correct or incorrect identification, precedes the identification process, such that less attentional resources are required for the simple detection than identification (Lavie, 1995; Joseph et al., 1997; Posner et al., 1980; Treisman & Gelade, 1980). Therefore, the probe-detection frequency, which requires at least simple detection, could assess proactive suppression more sensitively than the conventional probe-recognition frequency, which requires recognition. Specifically, the probe-recognition frequency may overlook attended probes that were detected but not entirely identified. In contrast, the probe-detection frequency has the capacity to capture such instances. This was evidenced in our study, where probe-recognition accuracy revealed lower accuracy for attended probes at the singleton than nonsingleton distractor. Moreover, the lower frequency of probe detection at the singleton than nonsingleton distractor location implies proactive suppression, despite the finding that the probe-recognition assumption was not valid.

In addition, correlation tests further confirmed the contribution of the probe-detection frequency to the probe-recognition frequency. The magnitudes of the probe-detection frequency effect and the probe-recognition frequency effect covaried across participants, suggesting that the less frequent attention towards the singleton than nonsingleton distractors contributed to the less frequent reporting of correct probes in the singleton than nonsingleton distractors. Relatedly, using event-related potentials (ERP), Gaspelin and Luck (2018) found that when the singleton distractor failed to capture attention, it elicited a distractor positivity (Pd) component, a neural index of proactive suppression (Luck, 2014; but see also Kerzel & Huynh Cong, 2023). The magnitude of the Pd component (which is related to the probe-detection frequency in reflecting early attentional selection) and the magnitude of the probe-recognition frequency effect covaried across participants. This suggests that the probe-recognition frequency effect reflects proactive suppression, consistent with the correlations between the probe-detection frequency and the probe-recognition frequency in the present study. As Gaspelin and Luck (2018) did not evaluate the probe-recognition assumption, the present study extends the previous finding of proactive suppression by demonstrating proactive suppression even in situations where the probe-recognition assumption is invalid.

Reactive suppression

The present study found that the probe-recognition assumption is invalid, showing the lower recognition accuracy of probes at the singleton than nonsingleton distractor location. Then, what led to the lower recognition accuracy in the singleton than nonsingleton distractors? One potential mechanism is reactive suppression for the singleton distractors (van Moorselaar & Slagter, 2020). Specifically, reactive suppression induces rapid disengagement of attention from a suppressed stimulus (Geng & DiQuattro, 2010; Godijn & Theeuwes, 2002; Moher et al., 2011). The very brief attentional-dwell-time can interrupt the identification of the stimulus (Bundesen & Harms, 1999; Shibuya & Bundesen, 1988). That is, participants appeared to use the reactive suppression mechanism to reduce interference from the singleton distractors if the proactive suppression mechanism had not operated properly. For example, the probes on the singleton distractors were reported occasionally (42% in the probe-detection frequency measurement), suggesting that participants did not always successfully inhibit the singleton distractors at the pre-attentive stage. That is, the singleton distractors captured attention on some trials. Then, the reactive suppression would operate to minimize the processing of the singleton distractors.

Relatedly, Geng and Duarte (2021) suggested that proactive and reactive suppression operate in concert to reduce the processing of distracting information. For example, it was found that when the proactive suppression for the singleton distractors does not occur so that they captured overt attention, eye fixation on the singleton distractors was rapidly disengaged (Geng & DiQuattro, 2010; Godijn & Theeuwes, 2002; Moher et al., 2011). Furthermore, Chang et al. (2023) explored how locations where a target infrequently appears are suppressed and suggested that the location-based suppression could be both proactive and reactive. Therefore, the two suppression mechanisms appear to work in concert for achieving a common task-goal.

One may question that the probe accuracy should be higher for the target than nonsingleton distractor because attention was more frequently captured by the target so that attention would dwell longer in the target. However, proactive suppression and reactive suppression are suggested based on semi-independent systems (Braver, 2012); therefore, frequency in capturing attention may not correlate with attentional-dwell-time. Furthermore, it was found that although stimuli capturing attention more frequently did not have longer attentional-dwell-time, indicating little correlation between attentional selection in the pre – and post-attentive stages (Koenig et al., 2017). To our best knowledge, there is no study investigating the attentional-dwell-time in the capture-probe paradigm. Future research will be needed for better understanding the relationships between proactive and reactive suppression.

Future research may more effectively address whether the finding of the lower recognition accuracy of probes for the singleton than nonsingleton distractors is a result of reactive suppression by using an eye-tracker to measure the duration of the eye fixation. It is important to emphasize, however, that the primary aim of this study was to evaluate the probe-recognition assumption not to extensively explore the reasons why the assumption could be invalid. The present study directly verified the invalidity of the probe-recognition assumption.

Dual control mechanisms

The complementary operation is closely related to the dual mechanisms of control model (Braver, 2012). According to the model, the attentional control system is unlikely to rely on a single control-mechanism, either a reactive or proactive control mechanism. Instead, the model points out that for successful cognition the attentional control system utilizes mixture of the proactive and reactive suppression strategies. The two distinct control mechanisms have different advantages and disadvantages so that complementary cooperation exists. For proactive control, goal representations are maintained in advance of their implementation, minimizing interference from internal or external sources of distraction. Therefore, the advantage of proactive control is that behaviours can be continually adjusted for successful accomplishment of task-goals. The disadvantage is that continuous maintenance of goal representations is strongly resource consuming. Therefore, available cognitive resources are considerably reduced for maintenance of other information held in working memory. For reactive control, goal representations are only activated when they are needed. The advantage of reactive control is that before reactive control operates, resources are free up so that other goals can be achieved effectively. The disadvantage is that reactive control is activated by detection of the trigger events. Accordingly, if the events are not sufficiently salient to detect, they may fail to reactivate goal representations.

By strengthening their advantages and making up for the weaknesses each other, the dual systems optimize information processing for successful completion of goals. In line with the dual mechanisms of control model, the present study corroborates previous findings by demonstrating that proactive suppression effectively inhibit attention towards a salient distractor (Gaspelin et al., 2015; Won et al., 2019). However, in the case of failure of implementing proactive suppression, the salient distractor captures attention so that reactive suppression complementally occurs, disengaging attention rapidly to reduce the processing of the unwanted stimulus (Geng & DiQuattro, 2010; Godijn & Theeuwes, 2002; Moher et al., 2011).

The theoretical implication of the present study is twofold. First, inconsistent with the probe-recognition assumption typically applied in the capture-probe paradigm, the probe-recognition accuracy can be different between the singleton and nonsingleton distractors. Second, proactive suppression remains evident even in cases where the assumption is invalid. Taken together, the different prob-recognition accuracies and the demonstration of proactive suppression indicate that the proactive and reactive suppression mechanisms appear to operate in a complementary way to minimize the interference of distracting information.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Ethical approval

Ethical approval was obtained from the university research ethics committee at Korea University.

Data availability statement

The data from the experiment are available at the Center for Open Science: https://osf.io/efg62.

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