

## Selective attention and response set in the Stroop task

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Response set membership contributes much to the interference in the color–word Stroop task. This may be due to selective allocation of attention to eligible responses or, alternatively, to greater inhibition of distractors that are not responses. In the present article, we report two experiments that were designed to adjudicate between these accounts. In Experiment 1, membership was manipulated on a trial-by-trial basis by cuing the possible responses for each trial. Response time (RT) was longer for distractors that corresponded to a cued, eligible response than to an ineligible one. This cuing effect was independent of the number of different responses. In Experiment 2, the distractor was cued on half the trials. Cuing the distractor decreased RTs on both incongruent and congruent trials. Vincentile analyses in both experiments revealed that the effects were constant throughout the entire RT distributions. These results suggest that response set effects arise because of selective allocation of attention to eligible responses.

Since the inception of modern attention research in the 1950s (e.g., Broadbent, 1958), the issue of whether attentional selection is early or late in perceptually based responding has played a central role in experimental research (for reviews, see, e.g., Pashler, 1998; Styles, 2006). By the 1970s, it was generally accepted that attentional selectivity may be early or late, depending on the prevailing circumstances. This view was exemplified by Broadbent's (1970, 1971; Broadbent & Gregory, 1964) distinction between "stimulus set" and "response set." Stimulus set refers to selection on the basis of a perceptual attribute, such as spatial location, color, shape, or temporal order. Response set refers to selection on the basis of the vocabulary of eligible responses. Broadbent recognized that task performance may require one or both of these kinds of selective attention, depending on the situation. Whereas attention research in the past few decades has intensively investigated aspects of stimulus set (e.g., Pashler, 1998; Styles, 2006), response set has been much less examined.

One of the tasks that has demonstrated the importance of response set is the color–word Stroop task (Stroop, 1935). In a common version of this task, participants have to name the ink color of congruent or incongruent color words (e.g., the words GREEN or RED printed in green ink). Response time (RT) is typically longer in the incongruent than in the congruent condition (see MacLeod, 1991, for a review)—a phenomenon henceforth called the *Stroop effect*. A major part of the interference caused by incongruent stimuli is specific to the members of the response set. In a classic study, Klein (1964) observed that color words

that were eligible responses produced approximately two times more interference than did color words that were not used as responses in the experiment. For example, if the ink colors were red and green, color-naming responses were much slower for the word GREEN in red ink than for the word BLUE in red ink. This effect of response set has been replicated in several studies (e.g., Glaser & Glaser, 1989; Proctor, 1978).

In the present article, we examined two different explanations for the response set effect. First, the response set effect may be due to selective allocation of attention to eligible responses at the response selection level (see Broadbent, 1970, 1971; Deutsch, 1977). In a prominent model of the Stroop task that was developed by Cohen, Dunbar, and McClelland (1990), attention to particular responses is achieved by placing eligible responses in a more responsive part of their activation curve. Likewise, in the WEAVER++ model of Roelofs (1992, 2003), selective allocation of attention at the response level is achieved by restricting the "selection space" to eligible responses. Only responses within this selection space are competing for selection. In this model, words that do not correspond to eligible responses may still yield some interference because they activate alternative responses in the selection space via conceptual links, but this interference is less than that for words that are part of the response set. Second, response set effects may arise if noneligible responses are inhibited before trial onset or, alternatively, if noneligible responses are more strongly inhibited than eligible ones during target processing (see Aron, 2007; Aron, Robbins, & Poldrack, 2004; Ridderinkhof, 2002a, 2002b;

Tipper, 2001; West & Alain, 2000). In either case, distractor words belonging to the response set will interfere more with the color-naming task than will the inhibited distractors that are not part of the response set. Selective allocation of attention to eligible responses or the inhibition of noneligible responses may arise either by instructions (i.e., by informing the participants of the stimuli to which they have to respond) or through experience with the stimuli in the course of the experiment itself.

Up to this point, we have used the term *response set effect*, but in fact, the response set influences response latencies in two different ways. In the remainder of the present article, we use the term *membership effect* for the finding that RTs are longer for incongruent distractors that correspond to eligible responses than for incongruent distractors that do not. At present, the exact factors that establish the membership effect are largely unclear (see MacLeod, 1991, 2005, for the color-word Stroop task, and Caramazza & Costa, 2001, and Roelofs, 2001, for the picture-word interference task). A major goal of the present article was to examine what mechanism is responsible for the effect of response set membership. In particular, we wanted to assess the relative merits of the attention allocation and inhibition accounts of this membership effect by using a modified Stroop task that includes cuing.

A second effect of response set that has been observed in the color-word Stroop task concerns the number of eligible responses. Evidence suggests that the number of allowed responses affects the difficulty of response selection (Cohen, Usher, & McClelland, 1998; see Kornblum, Hasbroucq, & Osman, 1990, for a review), hereafter called the *set size effect*. For example, Sternberg (1969) found that the set size interacted with stimulus-response compatibility. Unlike the membership effect, the direction in which the set size influences Stroop task performance is unclear. For instance, Nielsen (1975) observed that the magnitude of Stroop interference increased with an increasing number of responses—a finding that was replicated with the same set sizes by Kanne, Balota, Spieler, and Faust (1998). In contrast, Ray (1974) found that when the stimulus set size was increased, the overall RTs also increased, but that the Stroop effect was unaffected. To complicate the empirical picture further, La Heij, Van der Heijden, and Schreuder (1985) observed that increasing the response set led to a decreased Stroop effect. In his review of set size effects, MacLeod (1991) concluded that “although variations in response set size might be expected to affect interference, existing results are unclear” (p. 184) and that “until such discrepancies are resolved, it would be premature to offer a firm statement about stimulus set size effects” (p. 177). Therefore, a second goal of the present study was to further examine this set size effect in Stroop task performance.

In the WEAVER++ model of Stroop task performance (Roelofs, 1992, 2003), membership and set size influence different aspects of the response selection process. Whereas membership determines which responses compete for selection, set size determines the momentary selection probability of a response after it has been design-

ated as the response that will ultimately be given. In the model, this probability is a ratio of the activation of the target response and the sum of the activations of all other responses in a whole experiment or block of trials, regardless of response set membership (Roelofs, 1992, p. 118). The selection probability decreases with an increasing number of responses. Target designation and actual selection concern two temporally nonoverlapping phases of the response selection process in the model. Because membership and set size influence different aspects of response selection, their effects on RT should be additive.

We report two experiments that were designed to examine the relative merits of the attention allocation and inhibition accounts of membership effects and to investigate the effect of set size on RTs and the magnitude of the Stroop effect. In Experiment 1, response set membership was manipulated on a trial-by-trial basis while keeping the number of responses (set size) within an experimental block of trials constant. This was achieved by cuing the specific response set for each upcoming trial. That is, a cue presented before the color-word Stroop stimulus informed the participants about the two eligible responses for that particular trial. Either the distractor word was a member of the response set for that trial, or it was not. Furthermore, the set size was manipulated by presenting either three or six colors within a block of trials.

Although both the inhibition and the attention allocation accounts predict a membership effect and a set size effect, the effects are predicted to be interactive or additive, depending on the account. In particular, as we will point out below, the inhibition account predicts an interaction, whereas the attention allocation account predicts additive effects of response set membership and set size. In Experiment 2, we tested the inhibition account more explicitly by cuing the distractor in 50% of the trials. According to the inhibition account, these cued distractors may be inhibited, which should diminish the interfering effect of incongruent distractors (speeding up responses on cued incongruent trials) but also should diminish the facilitatory effect of congruent distractors (delaying responses on cued congruent trials) and thus reduce the magnitude of the Stroop effect. Importantly, RTs should be prolonged on cued as compared with uncued congruent trials. In contrast, if cuing the distractor allows for greater allocation of attention to eligible responses, this should reduce response latencies on both incongruent and congruent trials, as we will explain in more detail below.

Ridderinkhof (2002a, 2002b) argued that inhibition takes time to build up during target processing. Consequently, differences in inhibition should be largest in the tail of the RT distribution. Moreover, he assumed that the strength of the inhibition may be strategically adjusted depending on, for example, the previous trial type. Similarly, more inhibition may be applied to distractors outside than inside the response set. This predicts that the effects of response set membership (Experiment 1) and distractor cuing (Experiment 2) should be largest in the tail of the RT distributions. We tested these predictions by performing distributional analyses in both experiments.

## EXPERIMENT 1

The main goal of the first experiment was to test the attention allocation and inhibition accounts of the membership effect in the Stroop task. On each trial, stimulus presentation was preceded by a display of two small, colored rectangles, one of which always corresponded to the upcoming target ink color. The distractor word either could correspond to a cued color or did not match a member of the momentary response set. For example, assume that the possible colors in a block of trials are red, green, and blue. On a specific trial, a cue could indicate that the possible responses for that trial are "red" and "green"; that is, the upcoming target color is either red or green. The stimulus that is subsequently presented in red or green ink might then be, for example, the word GREEN (i.e., the distractor is in the response set) or the word BLUE (i.e., the distractor is not in the response set). In addition to the membership effect, we investigated the effect of set size. We therefore manipulated the number of eligible responses in a block of trials. Either three or six colors were used to create the color-word stimuli.

The two accounts make different predictions for the present experiment, concerning whether the effects of response set membership and set size are interactive or additive. According to the attention-allocation account instantiated by WEAVER++, a membership effect arises because of selective allocation of attention to eligible responses at the response selection level. A distractor that matches a cued response is inside the selection space for that trial and therefore interferes more with the response selection process than does a distractor that is outside the selection space. Moreover, an effect of set size should arise because the selection ratio (instantaneous selection probability) decreases with an increasing number of responses in a block of trials, increasing the RTs in the large set size as compared with the small set size condition. Importantly, since the membership effect in this view depends on the distractor type (i.e., distractor either inside or outside the response set) and the set size effect depends on the number of responses in a block of trials, the effects are predicted to be additive. Alternatively, according to the inhibition account, advance knowledge of the two eligible responses on a trial allows for inhibition of the other responses, which also should yield a membership effect. For instance, suppose that the colors red, green, and blue are used. A trial starting with a red-green cue could never have "blue" as a response and might thus lead to the inhibition of this response. As a result, less interference should be observed for incongruent stimuli in which BLUE is the distractor word (e.g., BLUE in red ink), than for incongruent stimuli in which either RED or GREEN is used as the distractor word (e.g., GREEN in red ink). Additionally, the inhibition of individual responses may be more difficult as the number of eligible responses increases, which should yield an effect of set size. Since, according to the inhibition account, the response "blue" (in the aforementioned example) will be inhibited less if the number of responses in a block of trials increases, the

account predicts an interaction between the membership effect and the set size effect.

## Method

**Participants.** Twenty-four Dutch students from Nijmegen University (20 of them female) volunteered to participate in the experiment. Their ages varied from 18 to 26 years, with a mean of 21 years. All had normal or corrected-to-normal vision. Participants either were paid or received course credit for their participation.

**Materials and Design.** The displayed stimuli consisted of written color words (capital letters, Arial font size 24 pt) in various ink colors. The stimuli words were centrally placed in an invisible rectangle that was  $42 \times 11$  mm (corresponding to  $3.4^\circ \times 0.9^\circ$  of visual angle at a viewing distance of approximately 70 cm). The distractor words were the following Dutch color words: ROOD (red), GROEN (green), BLAUW (blue), GEEL (yellow), BRUIN (brown), and PAARS (purple). The ink colors used in the experiment consisted of the six corresponding colors. The background of the computer screen was black.

There were 12 Stroop stimuli that were divided into two stimulus sets. The first stimulus set consisted of 3 congruent stimuli (ROOD in red ink, GROEN in green, BLAUW in blue) and of 3 incongruent stimuli (ROOD in blue, GROEN in red, BLAUW in green). The second stimulus set consisted of 3 other congruent stimuli (GEEL in yellow, BRUIN in brown, PAARS in purple) and of 3 other incongruent stimuli (GEEL in purple, BRUIN in yellow, PAARS in brown).

There were 12 cues, 6 for each of the two stimulus sets. The 6 cues for each set consisted of all possible pairwise combinations of colors in the set. For example, for the first stimulus set, the cues were red-green, red-blue, green-red, green-blue, blue-red, and blue-green. In a similar manner, the six cues for the second stimulus set consisted of all combinations of the colors yellow, brown, and purple. Each cue was made up of two colored bars, each measuring  $42 \times 11$  mm (corresponding to  $3.4^\circ \times 0.9^\circ$  of visual angle at a viewing distance of approximately 70 cm), placed vertically adjacent to each other with 1 pixel (about 0.5 mm) interspace.

There were three distractor conditions: congruent (CON), incongruent with the distractor word in the response set (INC-in), and incongruent with the distractor word not in the response set (INC-out). Furthermore, two set size conditions were used. In the small set size condition, stimuli consisted of only three colors (both distractor word and ink color), either the first or the second stimulus set described above. Thus, there were only three different responses in the small-set condition. The large set size condition employed all six colors from both stimulus sets together, resulting in six different responses in the large set size condition.

As was mentioned previously, we used a design in which each distractor word was written in only one nonmatching ink color and in which the cues and stimuli were divided into two subgroups. This was done for the following two (statistical) reasons. First, we wanted to have an equal number of congruent and incongruent stimuli while keeping the frequency of stimulus presentations equal. We achieved this by displaying, for example, ROOD in blue ink and never in green ink. Otherwise, if each distractor word were matched with each color, either keeping the stimulus frequency equal would lead to two thirds of the trials being incongruent, or presenting an equal number of congruent and incongruent trials would lead to displaying the ROOD-in-red stimulus twice as often as the ROOD-in-green and ROOD-in-blue stimuli. Second, we wanted to have an equal number of INC-in and INC-out trials. However, without our one-distractor-word-per-ink-color implementation, in the large set size condition with 36 stimuli (6 words  $\times$  6 ink colors), the two color bars in the cue would create one sixth CON trials, one sixth INC-in trials, and four sixths INC-out trials. In short, our present design makes it possible to have 50% CON trials, 25% INC-in trials, and 25% INC-out trials, while minimizing the chance of a confound with item repetition effects.

All of the participants were given both the small and large set size conditions. The order of set size conditions was counterbalanced across participants. Half of the participants started with the small set size, and the other half started with the large set size. The stimulus set in the small set size condition was randomly assigned to participants, with 12 participants receiving the first stimulus set and 12 participants receiving the second stimulus set.

Note that in this design, each cue can be followed by exactly four stimuli: two congruent and two incongruent ones. For example, a red–green cue can precede ROOD in red (CON), GROEN in red (INC-in), BLAUW in green (INC-out), and GROEN in green (CON) stimuli. Thus, 24 possible cue–stimulus combinations (6 cues  $\times$  4 stimuli) were formed for the small set size condition, and 48 combinations (12 cues  $\times$  4 stimuli) for the large set size condition.

An experimental session consisted of 48 practice trials and 480 test trials. The presentation of the 24 (in the small set size condition) or 48 (in the large set size condition) cue–stimulus combinations was pseudorandomized, with the following restrictions to reduce stimulus feature and response priming effects: A cue was never immediately repeated, and stimuli, distractor conditions, and responses were never repeated more than twice in a row.

**Apparatus.** The experiment was conducted on a microcomputer that was connected to two color monitors. The software package Nijmegen Experimental Setup Utility (NESU) Version 2004.12.1 was installed on the computer, which generated the visual displays and collected the experimental data. Vocal responses were measured with an accuracy of 1 msec (1000 Hz) by a voice key. The participants were seated in front of a color monitor at a viewing distance of approximately 70 cm. On a second monitor, the experimenter was shown the correct response and the participants' response latencies.

**Procedure.** The participants took part individually in a dimly illuminated, quiet room. The instruction for the first set size condition (small or large) was given on paper and was repeated orally by the experimenter. After 24 practice trials, 240 test trials followed, with a short break after the 120th trial. Then, the instruction for the second set size condition was given both written and orally. Again, 24 practice trials were followed by 240 test trials, with a short break halfway. When the color–word Stroop stimulus appeared, the ink color had to be named aloud. Participants were strongly encouraged to use the information about the upcoming target color that

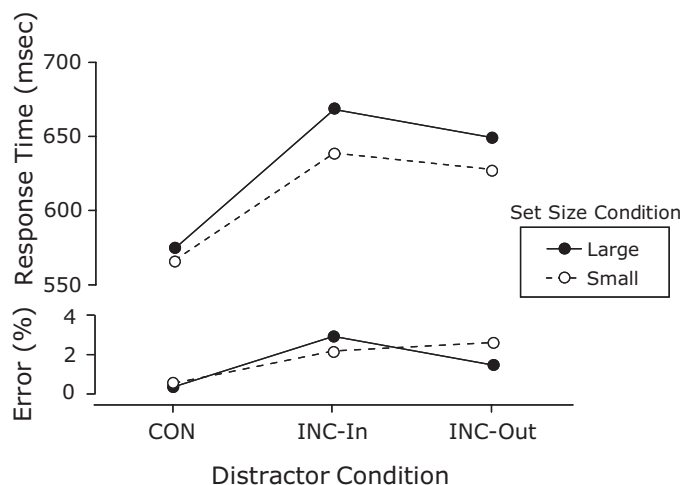
was provided by the cue and to react as quickly and as accurately as possible to the stimulus.

Each trial took 4.5 sec and went as follows. An empty screen was presented for 500 msec. Then a visual cue (two small color bars on top of each other) appeared at the center of the screen. After 250 msec, the cue disappeared, and the screen remained blank for 1,250 msec. Next, a color–word Stroop stimulus was displayed, also at the center. Incorrect responses and voice key errors were registered online by the experimenter. Although the stimulus disappeared after 1 sec, participants could respond for another 1,500 msec. Then the next trial started. The beginning of a break was indicated by the Dutch word PAUZE (“pause”) for 1,500 msec. The beginning of a block was preceded by the word ATTENTIE (“attention”) for 1,500 msec. Also, the start and the end of each set size condition were indicated by a short sentence such as EINDE DEEL 1 (“end of part 1”). An experimental session lasted about 1 h.

**Data analyses.** The following data-trimming procedure was used: Trials in which RTs were longer than 2,000 msec or shorter than 200 msec, trials in which the voice key malfunctioned or was triggered inappropriately (in combination, 1.10% of the data), and trials in which the participant made an incorrect response (1.37% of the data) were discarded. Also, to reduce posterror slowing effects (Rabbitt, 1966), each trial immediately following an incorrect response was omitted from analyses. To reduce start-up effects, the first three trials from each block were also discarded. The RTs of the remaining trials (93.6%) were used in calculations of means. The mean RTs were subjected to a two-way repeated measures ANOVA, with set size (small vs. large) and distractor condition (CON, INC-in, INC-out) as within-subjects factors. For the specific membership  $\times$  set size contrast, as formulated in the predictions, the congruent condition should be omitted, and therefore, only the incongruent distractor conditions (INC-in and INC-out) were included in the analyses. An alpha level of .05 was used for all statistical tests. The error rates given correspond to incorrect response trials only, not to voice key errors and time-outs. Because of the small number of errors, error rates were not further analyzed.

## Results and Discussion

The upper panel in Figure 1 shows the mean RTs as a function of distractor type for the small and large set



**Figure 1. Results of Experiment 1. Mean response times and incorrect response percentages as a function of distractor condition for the small and the large set size conditions. The within-subjects 95% confidence interval for the latencies is  $\pm 31$  msec. CON, congruent; INC-in, incongruent with distractor word in the response set; INC-out, incongruent with distractor word outside the response set.**

size conditions. The lower panel in Figure 1 shows the obtained error percentages for the same conditions. The figure shows that RTs were longer in the INC-in than in the INC-out condition and that responding in both conditions was slower than in the congruent condition. Moreover, RTs were longer in the large than in the small set size conditions on incongruent trials, but not on congruent trials. This set size effect appears to be independent of response set membership.

These observations were confirmed by the statistical analyses. A significant main effect of set size was observed [ $F(1,23) = 5.21, p = .032$ ], indicating that responses in the small set size condition (611 msec,  $SE = 19$ ) were faster than those in the large set size condition (630 msec,  $SE = 17$ ). The main effect of distractor condition was also significant [ $F(2,22) = 53.46, p < .001$ ]. Pairwise comparisons showed that congruent trials (571 msec,  $SE = 15$ ) were faster than both types of incongruent trials ( $ps < .001$ ) and that responses in the INC-in condition were slower than those in the INC-out condition (653 msec with  $SE = 21$ , and 638 msec with  $SE = 18$ , respectively,  $p = .010$ ). This indicates that we observed a membership effect.

In addition, a two-way interaction between set size (small vs. large) and distractor condition (CON, INC-in, and INC-out) was observed [ $F(2,22) = 8.21, p = .002$ ]. Post hoc tests revealed that for congruent trials, no difference in RT was observed between the large and small set size conditions ( $p = .33$ ), whereas responses in the large set size condition were slower than responses in the small set size condition for the INC-in condition ( $p = .007$ ) and the INC-out condition ( $p = .04$ ). In other words, increasing the set size increases response latencies for incongruent stimuli, but not for congruent ones. Specific contrast analyses showed that the RT difference between congruent and incongruent trials was more pronounced in the large set size than in the small set size for both the INC-in condition (Stroop effects of 93 msec in the large and of 72 msec in the small conditions,  $p = .001$ ) and for the

INC-out condition (Stroop effects of 74 msec in the large and of 61 msec in the small condition,  $p = .02$ ). Thus, a set size effect is observed: The magnitude of the Stroop effect becomes larger with an increasing number of responses.

As was mentioned above, to investigate the relationship between the membership effect and the set size effect, the congruent trials should be excluded from analyses. Without the congruent trials, the difference in RT between INC-in and INC-out trials was the same for the small and the large set size conditions (membership effects of 19 msec in the large and of 11 msec in the small condition,  $p = .198$ ), indicating that the magnitude of the membership effect is unaffected by the set size. This result agrees with the predictions of the attention allocation account.

Ridderinkhof (2002a, 2002b) maintained that effects of differential inhibition are most prominent in the tail of RT distributions. To evaluate this claim, we examined the whole RT distributions. To obtain the latency distributions, the rank-ordered latencies for each participant were divided into five equal bins (20% quantiles), and mean latencies were computed for each bin, separately for the RTs of the six combinations of distractor condition and set size. By averaging these means across participants, Vincentized cumulative distribution curves (Ratcliff, 1979) were obtained. Vincentizing the latency data across individual participants provides a way of averaging data while preserving the shapes of the individual distributions (for a similar approach, see Lamers & Roelofs, 2007; Roelofs, 2008; Schneider & Verbruggen, 2008).

Figure 2 gives the distributional plots for the three distractor conditions per set size. The figure shows that the membership effect remains constant throughout the latency range for both the small and large set sizes, whereas the Stroop effect generally increases with bin.

The distributional latencies were subjected to a repeated measures ANOVA with the within-subjects factors of set size (small vs. large), distractor condition (CON, INC-in, and INC-out), and bin (1–5). As with the overall

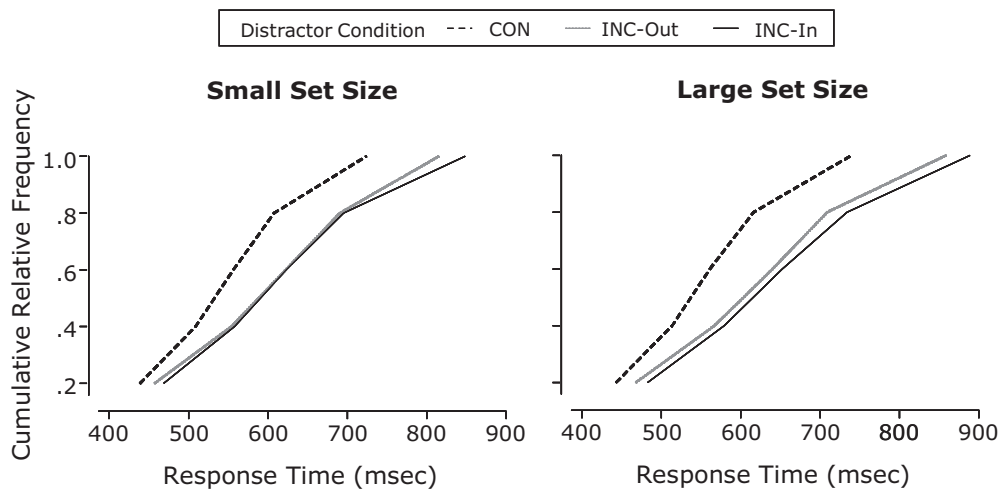


Figure 2. Vincentized cumulative distribution curves for the three distractor conditions for both set size conditions in Experiment 1. CON, congruent; INC-in, incongruent with distractor word in the response set; INC-out, incongruent with distractor word outside the response set.

RT analyses, the effects most important to the purpose of our study were both significant: A membership effect was observed in that responses in the INC-in condition were slower than those in the INC-out condition ( $p = .012$ ), and a set size effect was observed in that the magnitude of the Stroop effect was larger for the large set size than for the small set size ( $p = .001$  for the INC-in condition and  $p = .023$  for the INC-out condition). The other main effects and their interactions also closely resembled the analyses reported above on the mean RTs; therefore, only the results pertaining to the relative speed of responding are mentioned below.

The two-way interaction between distractor condition and bin was significant [ $F(8,16) = 10.32, p < .001$ ]. Post hoc tests revealed that the difference between INC-in and INC-out trials was similar for each bin ( $p > .05$ ), but that the difference between congruent trials and the two types of incongruent trials increased with bin (both  $ps < .001$ ). Put differently, the Stroop effect becomes larger with increasing response latencies, whereas the observed membership effect (the difference in RT between INC-in and INC-out trials) is unaffected by the relative speed of responding. The interaction between set size and bin was not significant [ $F(4,20) < 1$ ], showing that the magnitude of the difference in RT between the small and the large set size conditions was constant throughout the latency range.

As with the mean RT analyses, when focusing on the relationship between the set size (small vs. large) and the membership effect (INC-in vs. INC-out), the RT difference between INC-in trials and INC-out trials was equal for the small and the large set size conditions ( $p = .216$ ). Thus, both response set membership and set size increase the Stroop effect, but these effects are additive instead of interacting. The three-way interaction between set size, distractor condition (INC-in vs. INC-out), and bin was not significant [ $F(4,20) = 1.20, p = .34$ ], indicating that the additivity of membership and set size effects holds for every bin.

Let us summarize the findings above. First, a membership effect was obtained: The distractor word interfered more with color naming when this distractor belonged to the response set for the current trial (INC-in) than when it did not correspond to an eligible response in that trial (INC-out). This membership effect was observed in both the small and the large set size conditions, and the effect was unaffected by the relative speed of responding. Second, the results show a set size effect: The magnitude of the Stroop effect increased with increasing response set size. In particular, RTs in the incongruent condition (both INC-in and INC-out) were longer for the large set size than for the small set size, whereas RTs in the congruent condition were not influenced by set size. Third, membership and set size produced additive effects on RT, and the additivity was present along the entire RT distribution range.

Ridderinkhof (2002a, 2002b) argued that differential inhibition is most prominent in the tail of RT distributions. The membership effect was constant across the entire RT distributions in the present experiment. This suggests that the effect of membership is not caused by greater inhibition of distractors outside than inside the response set.

Whereas an effect of set size was present on incongruent trials, it was absent on congruent trials. In WEAVER++, alternative responses will be activated less on congruent than on incongruent trials. Consequently, the influence of the number of responses (set size) on the selection ratio will be less on congruent than on incongruent trials. This may explain why the effect of set size depended on distractor condition.

Note that we assumed that the inhibition of individual responses may be more difficult as the number of eligible responses increases. Although this seems intuitively correct, an alternative conclusion of Experiment 1 might be that inhibition is, in fact, not more difficult as the set size increases. In Experiment 2, we investigated the inhibition account in a different manner.

To conclude, an effect of response set membership and an effect of set size were observed, and the effects were additive. This corresponds with the predictions from the selective allocation of attention account and challenges the inhibition account. To further test the attention allocation and inhibition accounts, Experiment 2 was designed.

## EXPERIMENT 2

In the second experiment, we tested the two different accounts of the response set membership effect further by cuing the distractor word rather than the possible responses. Is Stroop task performance improved by having advance knowledge of the distractor word? Each color-word Stroop stimulus was preceded by one colored rectangle, which either matched the upcoming distractor word (the cued condition with a 100% valid distractor cue) or was an uninformative white (the uncued condition). For example, a cue could indicate that the distractor on the trial would be the word GREEN without providing any information about the possible responses (e.g., “red,” “green,” or “blue”). An equal number of congruent and incongruent trials was presented; thus, the cue gave no information about the upcoming target color (unless there is a learning effect, on which we focus in the General Discussion section). As in Experiment 1, participants were strongly encouraged to use the information provided by the cue to reduce the amount of Stroop interference.

If membership effects arise because noneligible responses are selectively inhibited, then, in the incongruent condition, knowing the distractor word and the corresponding noneligible response in advance should help color naming. However, the inhibition of the response corresponding to the cued distractor word may also have a detrimental effect on responding in the present experiment, because congruent Stroop stimuli are present as well. Consequently, the inhibition of the cued distractor response would reduce not only the interference from incongruent stimuli, but also the facilitation from congruent stimuli. Thus, for cued as compared with uncued trials, RTs for incongruent trials will be shorter, RTs for congruent trials will be longer, and the resulting Stroop effect will be smaller. The slowing of responding on cued congruent trials because of their inhibition may be offset

somewhat by a facilitatory effect from the color cue on recognizing the target color. Still, the Stroop effect (incongruent vs. congruent) is expected to be smaller for cued than for uncued trials. Moreover, if cuing allows for a greater inhibition of distractors and inhibition takes time to build up (Ridderinkhof, 2002a, 2002b), the effect of cuing on the Stroop effect should be largest in the tail of the RT distributions.

The predictions by the attention allocation account are different. As discussed by Cohen and Huston (1994), it is likely that bottom-up effects of attentional capture play a role in the Stroop task. The word may temporarily draw attention away from the color and thereby slow the response. Attentional capture is especially strong when stimuli are salient or unexpected (see, e.g., Corbetta & Shulman, 2002). Thus, distractor words may attract less attention when they are known in advance on the basis of the cue than when they are unknown in the uncued condition. Consequently, in the cued condition, more attention may be allocated to response selection, which should speed up responding on both incongruent and congruent trials. In addition, the speeding up of responding on cued congruent trials may be augmented somewhat by a facilitatory effect from the color cue on recognizing the target color. If so, the Stroop effect should be larger for cued than for uncued trials. Moreover, an effect of set size is predicted, as in Experiment 1.

Note that the assumption of attentional capture is an addition to WEAVER++. However, this assumption is sensible, because it has been previously proposed in the literature and it utilizes manipulations of attention, similar to the other aspects of WEAVER++. Attentional capture may also be assumed by the inhibition account. However, the inhibition of the cued distractor response would still reduce the interference from incongruent stimuli and the facilitation from congruent stimuli. Thus, the resulting Stroop effect would be smaller, regardless of attentional capture.

To summarize, the inhibition account predicts slower responding on congruent trials and faster responding on incongruent trials in the cued as compared with the uncued condition. The influence of cuing on the Stroop effect should be largest in the tail of the RT distributions (Ridderinkhof, 2002a, 2002b). In contrast, according to the attention allocation account, responding should be faster on both incongruent and congruent trials in the cued as compared with the uncued condition.

## Method

**Participants.** Twenty-four Dutch students from Nijmegen University (20 of them female) volunteered to participate in the experiment. Their ages varied from 18 to 28 years, with a mean of 21 years. All had normal or corrected-to-normal vision. The participants took part individually and either received course credit or were paid for their participation. None of the participants had taken part in Experiment 1.

**Materials and Design.** The displayed color-word Stroop stimuli were identical to the ones used in Experiment 1. As in the first experiment, the 12 stimuli were divided into two sets. Seven cues were used, consisting of one single, filled rectangle that measured  $42 \times 11$  mm (corresponding to  $3.4^\circ \times 0.9^\circ$  of visual angle at a viewing distance of approximately 70 cm). In the small set size condition,

red, green, blue, and white cues were used for the first stimulus set, and yellow, brown, purple, and white cues were used for the second stimulus set. In the large set size condition, all seven cues were used. As in Experiment 1, the background of the computer screen was black.

There were two distractor conditions: congruent (CON), in which the six stimuli for which ink color matched the distractor word, and incongruent (INC), in which the six stimuli for which ink color did not match the distractor word. Two cuing conditions were used. In the uncued condition, an uninformative white color bar preceded the Stroop stimulus. In the cued condition, a 100% valid color bar cue was presented that corresponded with the distractor word. As in Experiment 1, two set size conditions were used: a small set size (three colors) and a large set size (six colors).

An experimental session consisted of 48 practice trials and 480 test trials. The small set size condition consisted of 12 cue-stimulus combinations ( $3 \times$  CON-cued,  $3 \times$  INC-cued,  $3 \times$  CON-uncued,  $3 \times$  INC-uncued), whereas in the large set size condition, these numbers were doubled. These cue-stimulus combinations were pseudorandomized within a block of 24 trials, with the restriction that cues, stimuli, distractor conditions, and responses were never repeated more than twice in a row, to minimize stimulus feature and response priming effects. Because the initial item frequency in this experiment was not equally balanced (e.g., 50% of the trials used an uninformative cue), we controlled for the potential hazard of biases in these pseudorandomized item lists (see French & Peruchet, 2009).

**Apparatus and Procedure.** The apparatus configuration used in this experiment was identical to that in Experiment 1. Also, the procedure for this experiment closely resembled that in Experiment 1, except that the cue now gave information about the upcoming distractor word instead of the target color. The participants were encouraged to actively use this information to decrease the Stroop interference and to react as quickly as possible to the stimulus while retaining accuracy.

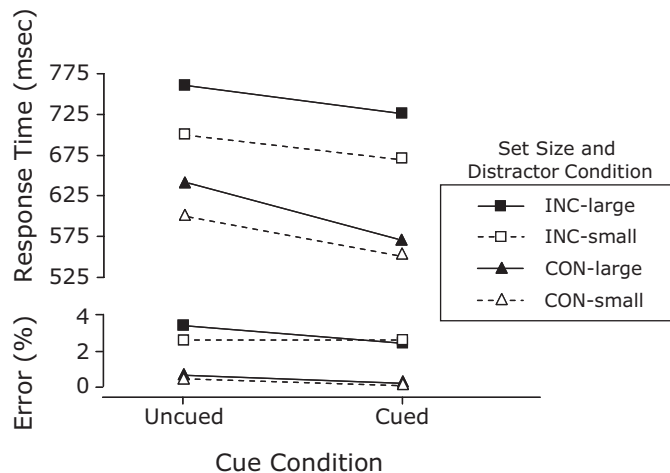
**Data analyses.** The same data-trimming procedure was used as in the first experiment. Outliers and voice key errors accounted for 1.0%, and incorrect responses accounted for 1.66% of the data. After removing the posterror trials and the first three trials of each block, the RTs of the remaining trials (93.2%) were used in calculations of means. Mean RTs were subjected to a repeated measures ANOVA with set size (small vs. large), distractor condition (congruent vs. incongruent), and cue condition (uncued vs. cued) as within-subjects factors.

## Results and Discussion

The upper panel in Figure 3 shows the mean RTs as a function of cue condition for the congruent and incongruent stimuli in both set size conditions. The lower panel in Figure 3 shows the obtained error percentages for the same conditions. The figure shows that RTs were longer on incongruent than on congruent trials, longer on uncued than on cued trials, and longer in the large than in the small set size condition.

Significant main effects were observed for all three factors. Responses in the small set size condition were overall 43 msec faster than those in the large set size condition [ $F(1,23) = 41.79, p < .001$ ], congruent trials were on average 122 msec faster than incongruent trials [ $F(1,23) = 304.1, p < .001$ ], and responses in the cued condition were 46 msec faster than those in the uncued condition [ $F(1,23) = 50.64, p < .001$ ].

All two-way interactions were found to be significant. They will be described in more detail below. The three-way interaction between set size, distractor condition, and cue condition did not reach significance ( $p > .05$ ).



**Figure 3. Results of Experiment 2. Mean response times and incorrect response percentages as a function of cue condition (cued vs. uncued) for the two distractor conditions (CON, congruent; INC, incongruent) in the small and the large set size conditions. The within-subjects 95% confidence interval for the latencies is  $\pm 30$  msec.**

A significant interaction between set size and distractor condition was observed [ $F(1,23) = 16.67, p < .001$ ]. The magnitude of the Stroop effect was larger in the large set size condition (139 msec) than in the small set size condition (105 msec); thus, the data indicate a set size effect. Post hoc tests showed that for both congruent and incongruent trials, responses were faster in the small set size condition than in the large set size condition, but this effect of set size was more pronounced for incongruent trials (a difference of 59 msec,  $p < .001$ ) than for congruent trials (a difference of 26 msec,  $p < .001$ ). This corresponds to the differential effect of set size on congruent and incongruent trials observed in Experiment 1.

A significant interaction between set size and cue condition was found [ $F(1,23) = 4.59, p = .043$ ]. Post hoc tests revealed that for both small and large set size conditions, responses in the uncued condition were slower than those in the cued condition ( $ps < .001$ ), but that this difference in RT between uncued and cued conditions was larger for the large set size condition (a cue effect of 54 msec) than for the small set size condition (a cue effect of 38 msec). In other words, the facilitatory effect on RTs from the cue becomes stronger with an increasing number of eligible responses.

Also, the interaction between distractor condition and cue condition was significant [ $F(1,23) = 17.04, p < .001$ ]. Post hoc tests showed that for both the cued and the uncued conditions, responses in the congruent condition were faster than those in the incongruent condition ( $ps < .001$ ), but the magnitude of this Stroop effect was larger for the cued condition than for the uncued condition (136 and 108 msec, respectively). This corresponds to the prediction of the attention allocation account and disagrees with the prediction of the inhibition account.

Note that these results clearly indicate that the cue indeed modified the response latencies. Theoretically, since the cue preceded a congruent Stroop stimulus in half of

the trials and an incongruent Stroop stimulus in the other half, participants could have chosen to ignore the cue as being uninformative about the target response. In that case, the cued and uncued conditions should have been similar, running opposite to the observed results.

As in Experiment 1, the predictions derived from the view on inhibition of Ridderinkhof (2002a, 2002b) were tested by performing distributional analyses. A repeated measures ANOVA was performed with set size (small vs. large), distractor condition (congruent vs. incongruent), cue condition (cued vs. uncued), and bin (1–5) as within-subjects factors. Figure 4 shows the distribution plots per set size. As indicated by the figure, the effect of the cue is present throughout the latency range in both the congruent and incongruent conditions and in the small and large set size conditions.

Again, only the results pertaining to the relative speed of responding will be reported here. For the factors of set size and distractor condition, significant interactions with bin were observed [ $F(4,20) = 3.07, p = .04$ , for the interaction between set size and bin, and  $F(4,20) = 13.30, p < .001$ , for the interaction between distractor condition and bin]. The effect of set size was significant for each bin, but the difference between small and large set size was somewhat larger for the outer bins. The effect of distractor condition was significant for all bins, but the difference between congruent and incongruent trials (i.e., the Stroop effect) increased with increasing bin. The interaction between cue condition and bin was not significant [ $F(4,20) = 1.95, p = .14$ ].

The significant interactions between set size and distractor condition, between cue condition and distractor condition, and between set size and cue (as also observed in the mean RT analyses) were similar for all bins, as was indicated by the nonsignificant three-way interactions with bin (all  $ps > .05$ ). In other words, for the entire latency range, the Stroop effect was larger for the large set size

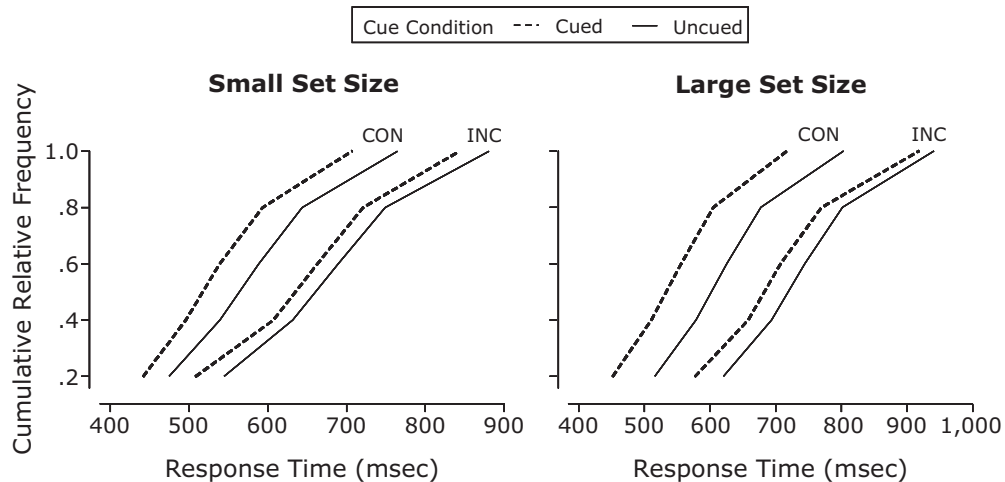


Figure 4. Vincentized cumulative distribution curves for the distractor (CON, congruent; INC, incongruent) and cue conditions for both set size conditions in Experiment 2.

than for the small set size and was larger for the cued condition than for the uncued condition. Similarly, the four-way interaction with bin was not significant [ $F(4,20) = 1.71, p = .188$ ]. Thus, the predictions for the inhibition account derived from Ridderinkhof (2002a, 2002b) are not supported by the data.

To summarize, the results indicate that cuing the distractor speeds up responding on both congruent and incongruent trials in both set size conditions. In addition, the Stroop effect was larger for the cued condition than for the uncued condition. These results support the attention allocation account and challenge the inhibition account. If membership effects arise because noneligible responses are selectively inhibited, then knowing the distractor word and the corresponding response in advance should help color naming by inhibition of the response corresponding to the distractor. In the present experiment, responding on incongruent trials was indeed faster when the distractor was cued as compared with when it was not. However, responding was also faster on cued congruent trials than on noncued ones, even though inhibition should have diminished the facilitation from congruent trials. This suggests that the inhibition account cannot explain the cuing effect. In contrast, the results confirm the predictions that were derived from the attention allocation account.

## GENERAL DISCUSSION

A major part of the interference observed in the color-word Stroop task is specific to the members of the response set (e.g., Glaser & Glaser, 1989; Klein, 1964; Proctor, 1978). This membership effect may be due to selective allocation of attention to eligible responses or to a greater inhibition of distractors that are not eligible responses. Two experiments were reported, in which we examined the relative merits of these two accounts. In Experiment 1, response set membership was manipulated on a trial-by-trial basis by cuing two possible responses for each trial. A membership effect was observed: Distractors that cor-

responded to a cued response yielded longer RTs than did distractors that did not, independently of the relative speed of responding. Moreover, the membership effect was independent of set size. In Experiment 2, on each trial, either the distractor was cued or the cue provided no advance information. Cuing the distractor decreased color-naming latencies on both incongruent and congruent trials. The decrease of RTs on congruent trials suggests that knowing the distractor does not result in greater inhibition. Taken together, the results of Experiments 1 and 2 provide evidence that response set membership effects arise because of selective allocation of attention to eligible responses. Furthermore, the manipulation of response set size in both experiments indicated that the Stroop effect increases with increasing set size and that this mainly results from increases in RTs for incongruent stimuli.

In Experiments 1 and 2, we employed a cuing paradigm. In contrast, such cues are not used in normal Stroop experiments. This raises the question of how the findings from the present cuing experiments relate to normal uncued Stroop task performance. In his classical study on membership effects using cards with 80 printed items, Klein (1964) found that the Stroop effect was twice as large for distractor words that corresponded to eligible responses than for distractor words that were outside the response set. In the present Experiment 1, the response set membership effect was much smaller. However, these studies differ on many points that likely influence the magnitude of the membership effect. The most prominent difference is that Klein used highly frequent color words for the distractors corresponding to the response set (red, green, yellow, and blue) and less frequent color words for the distractors outside the response set (tan, purple, gray, and black), whereas color name frequency was more balanced in our experiment. Klein already observed that the magnitude of the Stroop effect increases with word frequency. Indeed, when the stimuli were controlled for word frequency and association, Proctor (1978) observed a 24- to 30-msec increase in RT for words in the response

set (INC-in) compared with words that were not (INC-out). Likewise, using a picture–word variant of the Stroop task, La Heij (1988) observed membership effects of 13–27 msec. These magnitudes resemble our results in Experiment 1. The simplest explanation for the similarity in effects between normal uncued Stroop experiments (La Heij, 1988; Proctor, 1978) and the present cued experiment is that the cued and uncued response set effects are caused by the same mechanism—namely, selective allocation of attention to eligible responses in response selection.

Previous studies have painted no clear picture on the set size effect (see MacLeod, 1991). Studies with a varying number of possible responses found that when the set size was increased, the amount of Stroop interference increased (Kanne et al., 1998; Nielsen, 1975), remained unaffected (Ray, 1974), or decreased (La Heij et al., 1985). A possible explanation for this discrepancy in findings might be found in the particular range of response set sizes that was used for each study. Adamson, Foster, and McEwan (2000) demonstrated that for memory tasks (in particular, the delayed-matching-to-sample task), an increasing set size led to decreased task performance for small set sizes only. For larger set sizes, increasing the response set size had no effect. The same could hold for Stroop performance. Kanne et al. and Nielsen used set sizes 2, 3, and 4; Ray had three versus five eligible responses; and La Heij et al. varied the set size from 2 to 12. Thus, one could speculate that increasing the number of eligible responses within the lower boundaries of the set size range (2–4) results in an increase of interference; for intermediate set size levels (4–5), it has no effect; and, for large set size ranges (6 and up), increasing the set size is accompanied by a reduction in Stroop effect. Yet the exact boundaries are not clear. In our experiments, we found that the Stroop effect increased with increasing set size, corresponding to the findings of Nielsen, but with set sizes more closely resembling those of Ray. To vary set size parametrically was beyond the scope of the present study, however.

In Experiment 1, two eligible responses were cued for each trial, making up the momentary response set for that trial. We stated that the inhibition account predicts that perceiving the two cued colors can lead participants to inhibit the other responses within a set size condition. Thus, in the small set size condition, one out of three responses can be inhibited, whereas in the large set size condition, four colors can be inhibited as being ineligible. In Experiment 2, we predicted that participants might be able to inhibit the distractor word when it was cued before the stimulus appeared. The predictions concerning RT depend on how long such inhibition lasts. We assumed that it would last for a couple of seconds and, therefore, be more or less restricted to one trial (lasting 4.5 sec). Indeed, for inhibition of return effects (i.e., the suppression of processing of targets that have recently been the focus of attention), Samuel and Kat (2003) demonstrated, in a meta-analysis of its time course, that the effect of inhibition was robust for approximately 3 sec and that it appeared to taper off after this point. However, the hypothetical inhibition process referred to in the present article might have other un-

derlying dynamics, and it is possible that the cue-based inhibition effect in our experiments remains present for a longer period and therefore influences later trials as well. Moreover, we assumed that inhibiting ineligible responses (Experiment 1) depends on the same process as inhibiting a known distractor (Experiment 2), but that does not have to be the case. However, regardless of the inhibition dynamics and differences between ineligible responses and known distractors, our present experiments suggest that inhibition is not the mechanism causing the response set effects.

In Experiment 2, we used a color patch instead of a word to cue the upcoming distractor. We did this to minimize the design difference between the two experiments. One might argue that a color cue could also perceptually prime the upcoming ink color, even though participants are explicitly told that a congruent stimulus appears in only 50% of the trials. In congruent trials, this would lead to faster responses in the cued condition than in the uncued condition, as we observed. However, in that case, more interference should be observed for incongruent stimuli in the cued condition than in the uncued condition.<sup>1</sup> As Figure 3 illustrates, the opposite pattern was found.

In Experiment 2, we observed that the response latencies were shorter in the cued than in the uncued condition, even for congruent stimuli. We argued that this RT pattern is the result of the allocation of attention to the target and away from the distractor. However, there is an alternative explanation that is based on a possible learning effect. As was previously pointed out, in order to avoid creating an unbalanced number of INC-in and INC-out trials in Experiment 1, we decided to divide the six colors into two subgroups and to use only one nonmatching color word for each of the six incongruent stimuli. Especially those participants who started with the small set size condition (that used only one subgroup with three colors) could have learned the color–word combinations for the incongruent stimuli (e.g., the word *ROOD* can be presented in red or blue ink, but never in green ink). In that case, accidentally, the target cue in Experiment 1 also gave information about the upcoming distractor word (e.g., a red–green cue gives 50% chance of the word *GROEN* and a 25% chance each of *ROOD* and *BLAUW* and cannot be followed by the distractor words *BRUIN*, *GEEL*, and *PAARS*). This probably has no significant effect on the findings of Experiment 1, since the results of Experiment 2 indicate that even 100% valid information about the upcoming color word does not lead to inhibition of the distractor. However, in Experiment 2, such learned color–word relations could have improved overall RTs in the cued condition. For example, a red cue indicates then not only that the distractor will be *ROOD*, but also that the ink color will be either red (congruent) or blue (incongruent). Consequently, the distractor cue could selectively allocate attention to these two responses, thereby decreasing response latencies for both congruent and incongruent stimuli in the cued condition, in accord with our findings. Note that this alternative explanation for the findings in Experiment 2 involves some extra processing steps to be performed: (1) to infer during the experiment the various ink color–distractor word relations

and store this information in memory; (2) to perceive the color bar that indicates the upcoming distractor word and, unless this cue is white, retrieve from memory the non-matching ink color that is linked to this distractor; (3) to allocate attention to both the color response that was cued (in case the upcoming stimulus will be congruent) and the color response that was retrieved from memory (in case the upcoming stimulus will be incongruent).

To investigate whether such a learning effect was present in Experiment 2, we reanalyzed the data. We hypothesized that response latencies for cued-congruent trials would differ more from those for uncued-congruent trials (e.g., showing a larger learning effect) when participants had more opportunity to learn the color–word relations, either by having started with the small set size condition or through accumulative evidence gathering during the experiment. We performed a repeated measures ANOVA with set size (small vs. large), cue condition (cued vs. uncued), and block half (first half vs. second half within a certain set size condition) as within-subjects factors, and the order of the set size condition (small–large vs. large–small) as a between-subjects factor. The results showed that neither the interaction between cue and order ( $p = .134$ ) nor the interaction between cue and block half ( $F < 1$ ) was significant. Thus, no support for the learning hypothesis was found.

Still, the fact that these two interactions were not significant could simply be due to a lack of statistical power. Therefore, we performed a second analysis on the data of Experiment 2 in search of a possible learning effect concerning ink color–distractor word relations. For the 12 participants who started with the small set size condition, we divided the trials from the large set size condition into two data sets—one with the “old” stimuli that were used before in the small set size condition, and one with the “new” stimuli that had not been presented before to these participants (i.e., the three colors from the second subset). If the observed cuing effects in Experiment 2 (see Figure 3) were in fact caused by learned associations, then logically, these cue effects should be larger for the old stimuli than for the new stimuli. The results showed numerically the opposite: In the congruent condition, the cue decreased the RTs by 61 msec for the old stimuli and 69 msec for the new stimuli. Similarly, in the incongruent condition, the cue decreased the RTs by 26 msec for the old stimuli and by 30 msec for the new stimuli. This provides strong evidence against an alternative explanation for the results of Experiment 2 based on learned associations.

To summarize, when response set membership is manipulated on a trial-by-trial basis, a membership effect arises, independently of set size and relative speed of responding. Moreover, cuing the distractor decreases color-naming RTs on both incongruent and congruent trials. The observation that RTs on congruent trials are shorter and the Stroop effect is larger in the cued condition suggests that knowing the distractor does not result in greater inhibition. Taken together, these results provide evidence that response set effects arise because of selective allocation of attention to eligible responses. Increasing set size from three to six leads to an increase of RTs, more so for

incongruent than for congruent stimuli. Thus, the present findings support Broadbent’s (1970, 1971) assumption that attention can be selectively allocated to eligible responses, as implemented in the WEAVER++ model.

#### AUTHOR NOTE

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## NOTE

1. Note that for priming of the cue color to produce slower responses, cross-modal priming is needed. If priming is only within vision, then the congruent condition would be facilitated and the incongruent condition unchanged. However, the results indicate that for incongruent trials, the cue led to faster responses.

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