Response control by primes, targets, and distractors: From feedforward activation to controlled inhibition

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This is a post-peer-review, pre-copyedit version of an article published in ***Psychological Research.*** *The final authenticated version is available online at* https://doi.org/10.1007/s00426-019-01236-9

Abstract

The visual system has to distinguish between information that is relevant versus irrelevant for current behavioral goals. This is especially important in automatized responses. Here we study how task-irrelevant distractors with task-relevant features gain access to speeded, automatized motor responses in a response-priming paradigm. In two tasks, we present distractors either together with primes or with targets, and vary the consistency between primes/targets and distractors as well as the number and saturation of distractors. Our findings are consistent with accounts where primes, targets, and distractors contribute to response activations by sequential feedforward response activation. In addition, conditions with especially salient target distractors seem to lead to active inhibition of the primed response that occurs late in the trial. We replicate all main findings in a control experiment. Together, our findings show that the effects of distractors depend on (i) their stimulus characteristics as well as on (iii) the phase at which they enter visual processing–with effects ranging from feedforward activation to controlled inhibition of responses.

Keywords: response priming; response inhibition; singleton effect; interference effect; redundancy gain

1. Introduction

1.1. Perceptual priming and distractors

Most of the time, we are confronted with many visual objects and stimulus features, some of which are relevant for our current behavior and some of which are not. Responding to relevant objects is especially demanding in tasks in which we are prepared to respond quickly and automatically to features of relevant objects while similar features in irrelevant objects have to be excluded from action control. An everyday example for such a filtering problem is driving a car on a crowded highway. When the stoplights of the car in front of us are flashing up, we might show an automatized response to reduce speed or even hit the brake. At the same time, all similar stimulus events (e.g., a pedestrian light turning red, a signal appearing on the dashboard) have to be ignored. In other words, distractors that are actually task-irrelevant may possess features that do fit the task's stimulus-response mapping and could therefore access the response. How do such distractors affect our automatized responses? Which features of the distractors modulate these effects?

1.2. Response priming paradigm

Here we study how task-irrelevant distractors with task-relevant features gain access to speeded, automatized motor responses in a response-priming paradigm. *Response priming* is a method to study rapid visuomotor processing (T. Schmidt et al., 2011). In each trial, observers respond to a target stimulus as quickly and accurately as possible (e.g., left button for red target; right button for green target). The target is preceded by a prime stimulus which is either mapped to the same response as the target (*consistent prime*; e.g., red target preceded by red prime) or to the alternative response (*inconsistent prime*; e.g., red target preceded by green prime). Typically, consistent primes will speed responses to the target and produce fewer errors while inconsistent primes will slow responses and produce more errors. This difference between response times or error rates in consistent versus inconsistent trials is labeled the *priming effect*.

The magnitude of this priming effect is influenced by a number of variables. The most prominent one is the stimulus-onset asynchrony (SOA), that is, the time between the onsets of prime and target. The typical response priming effect, in which we are interested here, occurs for SOAs up to about 100 ms and increases approximately linearly with SOA (e.g., Jacob, Breitmeyer, & Trevino, 2013; Vorberg, Mattler, Heinecke, T. Schmidt, & Schwarzbach, 2003). Accumulator models of response priming (Vorberg et al., 2003; cf. Mattler & Palmer, 2012; T. Schmidt & F. Schmidt, 2018; Schubert, Palazova, & Hutt, 2013) assume that the prime starts activating the response assigned to it, followed by response activation by the actual target after the SOA. Depending on whether the prime is consistent or inconsistent with the target, it will drive the response process into either the correct or incorrect direction, and may even cause a response error. The longer the SOA, the more time is available for the prime to activate the response when the target is further delayed, and the larger the priming effect in both response times and error rates (Flannigan, Chua, & Cressman, 2016; Klotz, Heumann, Ansorge, & Neumann, 2007; Leuthold & Kopp, 1998; T. Schmidt, 2002; Vath & T. Schmidt, 2007). Response priming is closely related to the flanker paradigm (Eriksen & Eriksen, 1974; Schwarz & Mecklinger, 1995), which is probably based on the same mechanism of response conflict between flankers and targets (T. Schmidt, Haberkamp, & F. Schmidt, 2011). For instance, both effects increase with SOA, and both effects produce fast response errors in inconsistent trials.

1.3. The role of stimulus saliency

Another variable affecting the magnitude of priming effects is the saliency of primes and targets. Only a few studies tested the role of stimulus saliency in response priming paradigms. F. Schmidt and T. Schmidt (2013) studied priming effects induced by displays of horizontal or vertical orientation and varied the saliency of this orientation by increasing or decreasing stimulus contrast. As a general rule they found that more salient primes produced stronger priming effects, and more salient targets produced faster responses. Findings by Vath and T. Schmidt (2007) and F. Schmidt, Weber, and T. Schmidt (2014a) support this rule when using primes of varying color saturation. Generally, all of these findings are in accordance with our own accumulator model, which allows prime and target to have different activation rates (T. Schmidt & F. Schmidt, 2018). It predicts that stronger primes increase the priming effects, while stronger targets decrease response times and priming effects. Other studies report similar effects of variations in saliency and show, for example, that priming effects are diminished by pattern masking of the primes (e.g., Eimer & Schlaghecken, 2002) or by partly obscuring response-relevant prime features (e.g., F. Schmidt, Weber, & T. Schmidt, 2014b). On the other hand, priming effects are remarkably unaffected by metacontrast masking (Vorberg et al., 2003).

In all these studies only the target is task-relevant. The prime is actually task-irrelevant but has features that fit a stimulus-response scheme of the task, thereby creating a motor conflict if prime and target trigger different responses (Kunde, Kiesel, & Hoffmann, 2003; Neumann, 1990). Our approach here is to employ additional distractor stimuli to see how they modulate this motor conflict. We implement a response priming paradigm with color targets (red or green) preceded by either consistent or inconsistent color primes. In two different tasks, distractors appear simultaneously with either the primes or the targets. They are either consistent or inconsistent in color with the respective stimulus (prime or target). For this setup, we consider the following hypotheses (overview of hypotheses, predictions, and results in Table 1 in the General Discussion section).

1.3.1. Singleton hypothesis. A first hypothesis can be derived from the *singleton effect*. Visual search experiments show that task-relevant color singletons (e.g., a red element among several green elements) capture attention even when masked (Ansorge, Horstmann, & Worschech, 2010). This suggests that the saliency of primes and targets would be enhanced by distractors of a different color, and reduced by distractors of the same color, for instance by simultaneous contrast (e.g., Kaneko, Anstis, & Kuriki, 2017; Maljkovic & Nakayama, 1994) or mutual inhibition of color-opponent channels (Gegenfurtner & Kiper, 2003). For example, a red prime surrounded by green distractors should be more salient (i.e., produce larger priming effects in response times and error rates) than a red prime surrounded by red distractors. It should then activate its associated response at an elevated rate, leading to larger priming effects. Equivalently, a red target surrounded by green distractors should be more salient (i.e., produce faster responses) compared to a red target surrounded by red distractors. Its elevated rate of response activation should lead to faster overall responses.

1.3.2. Crowding hypothesis. A second hypothesis is that the distractors *interfere* with the processing of the prime or target. An example of this is the *crowding effect*, where the recognition of visual stimuli (presented outside the fovea) is impaired by the presence of neighboring stimuli (e.g., Levi, 2008). The standard crowding hypothesis makes straightforward predictions only for neutral (grey) distractors. Provided that crowding occurs in rapid visuomotor processing, prime saliency should be reduced by neutral distractors presented at the time of the prime, resulting in weaker response activation by the prime and therefore smaller priming effects. Equivalently, target saliency should be reduced by neutral distractors presented at the time of the target, resulting in larger priming effects and slower responses. More recent updates of the crowding hypothesis would also make straightforward predictions for color distractors based on the perceptual (color) grouping of distractors and primes/targets (Francis, Manassi, & Herzog, 2017). According to this account, prime and target saliency would be reduced especially by consistent distractors of high saturation, which could perceptually group with primes/targets either because of their color similarity or because they form a global object (Manassi, Sayim, & Herzog, 2012). Reduced saliency of primes or targets should then result in smaller priming effects or larger priming effects and slower responses, respectively. Inconsistent distractors, on the other hand, should release the primes/targets from crowding.

Similar predictions would follow from *perceptual load theory* (Lavie, 1995, 2005). In a typical experimental paradigm on perceptual load (Lavie & Cox, 1997), participants have to identify which of two pre-specified letters (e.g., *N* or *X*) is presented in the current trial. When the central target (e.g., *N*) is presented together with a peripheral distractor, responses are typically faster with a consistent distractor (e.g., *N*) compared to an inconsistent distractor (e.g., *X*). This consistency effect is modulated by the amount of perceptual load, which is varied by presenting additional letters either dissimilar (low load) or similar to the target (high load): The difference between consistent and inconsistent trials is larger when perceptual load is lower, and smaller when load is higher. This effect was also demonstrated in repetition priming (Lavie, Lin, Zokaei, & Thoma, 2009). Perceptual load theory makes straightforward predictions for our paradigm. If perceptual load is relevant for rapid visuomotor processing, priming effects should be larger when perceptual load is low, that is, with no or few and inconsistent distractors presented at the time of the prime. Conversely, priming effects should be smaller when perceptual load is high, that is, with many consistent distractors. For distractors at the time of the target, overall responses should be faster under low perceptual load and slower under high load.

1.3.3. Motor access hypothesis. A third hypothesis is that the distractors gain *access to the motor system* much like the primes and targets do, so that they create their own response priming effect. This hypothesis can be derived from the well-known response-time advantage of multiple identical stimuli compared to a single stimulus (*redundancy gain*; e.g., Corballis, 2002). This effect is predicted by models assuming parallel processing of all targets until the first channel has completed processing (*race models*; e.g., Colonius & Vorberg, 1994; Miller, 1982; Raab, 1962), or alternatively by sensorimotor facilitation (*coactivation models*; convergence of stimulus signals onto the same response; e.g., Miller & Ulrich, 2003; Townsend & Nozawa, 1995). With both mechanisms, distractors of the same color as the primes should produce larger priming effects, and distractors of the same color as the targets should produce faster responses compared to distractors of different color. All these effects should increase with distractor number and saturation.

2. Experiment 1

2.1. General

We investigated the role of distractors during target and prime presentation, respectively. Participants responded to the color (red or green) of a single target stimulus that could appear at different monitor locations. The target was preceded by a brief prime stimulus at the same location. The prime was either red or green, thus mapped to either the same response as the target (*consistent prime*) or to the other response (*inconsistent prime*), with the prime-target SOA varying between 27 and 67 ms. On each trial, either no, one, or seven distractors appeared. Distractors varied in color saturation and appeared either during target presentation (*target distractor task*) or prime presentation (*prime distractor task*). Having shapes like primes, distractors differed from targets in their shape, and always had lower saturations than both primes and targets. Depending on their time of presentation, we speak of *target distractors* or *prime distractors*, respectively. If distractors appeared, they were either all a neutral gray, all of a color consistent with the stimulus they accompanied (*prime-consistent, target-consistent distractors*), or all of a color inconsistent with the stimulus they accompanied (*prime-inconsistent, target-inconsistent distractors*). We were interested in several questions (Table 1).

First, we wanted to know whether distractors different in color (from the prime or target they accompany) increase the motor impact of the respective stimulus, e.g., by increasing its saliency (*singleton hypothesis*) or decreasing perceptual load. If so, priming effects in response times and error rates should increase with increasing color contrast between primes and prime distractors, and response times should decrease with increasing color contrast between targets and target distractors.

Second, we wanted to know whether neutral (gray) distractors diminish response activation by the primes or targets they accompany (*crowding hypothesis*). If so, neutral distractors during prime presentation should diminish the priming effect in response times and error rates, whereas distractors during target presentation should slow down responses with increasing number of distractors.

Third, we were interested in the possibility of motor activation by the distractors themselves (*motor access hypothesis*). Specifically, if simultaneous primes and distractors activated their associated responses independently, we would expect prime-consistent distractors to amplify the effect of the primes, and prime-inconsistent distractors to diminish the effect of the primes. Likewise, target-consistent distractors should speed responses whereas target-inconsistent distractors should slow responses. The observed effects of distractors on response priming and response times should be modulated by the number and saturation of the distractors.

2.2. Methods

2.2.1. Participants. Eight students from the University of Kaiserslautern, Germany (three of them male), with normal or corrected vision participated in the experiment for financial compensation (6 €/h). Due to loss of a record sheet, we cannot reconstruct their exact age and handedness, but all participants were in their twenties, and left-handers were allowed to participate. Sample size was based on previous studies using similar experimental paradigms (e.g., F. Schmidt & T. Schmidt, 2013; F. Schmidt et al., 2014b). All participants gave informed consent, were debriefed after the experiment, and treated according to the ethical guidelines of the American Psychological Association. All testing procedures were carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.2.2. Apparatus and Stimuli.The participants were seated in a dimly lit room in front of a color monitor (1280 x 1024 pixels) with a monitor retrace rate of 75 Hz at a viewing distance of approximately 50 cm. Stimulus presentation was controlled by MATLAB using the Psychophysics Toolbox extension (Kleiner, Brainard, & Pelli, 2007). In both tasks, the fixation point was a small white circle (diameter: 0.17°; 1 cm ≈ 1.15° of visual angle) at the center of the screen; all stimuli were placed on a uniform black background.

Primes were disks with a diameter of 0.71° of visual angle presented at one of four corners of an imaginary 3.40 × 3.40 cm square (3.90° × 3.90° of visual angle), centered on fixation (Figure 1). Targets were annuli with an outer diameter of 1.13° and an inner diameter exactly the size of the primes, and were presented at the same position as the primes. Distractors were disks of the same size as the primes and were either presented at the opposite corner of the square (one distractor) or at the three other corners and at the midpoints of each side of the square (seven distractors).

Primes and targets were isoluminant red or green (22.87 cd/m²), with isoluminance defined in the CIELAB color space (CIE, 1978). This color space is designed to approximate human vision and its parameters reflect red-green visual opposition (a*), yellow-blue visual opposition (b*), and lightness (L*). All stimulus parameters were measured with a spectroradiometer (SpectroCAL, Cambridge Research Systems, Kent, U.K.) and chosen such that b* and L* were constant. Distractor stimuli were either red or green at three different levels of saturation. They were always less saturated than primes and targets. The first level of the least saturation was of the same uniform grey for both colors with L* = 54.46 (24.09 cd/m²). The second and third level of increasing saturation were chosen to be equidistant in a* ($d \approx 11.12$). The resulting a* parameters for red were 30.51 and 19.39, those for green were -30.51 and -19.39. Higher saturated primes and targets had a* parameters of 41.64 for red and -41.64 for green.

2.2.3. Procedure. Each participant performed four 1-hour sessions of a response priming task. In each session, they responded to 720 experimental trials of the prime distractor task and the target distractor task, respectively, adding up to 5,760 trials per participant. The order of both tasks was counterbalanced across sessions and participants. Sessions were organized into a practice block followed by 24 experimental blocks of 30 trials each. After each block, we provided participants with summary feedback on their response times and error rates.

2.2.3.1. Target distractor task. The experimental procedure is illustrated in Figure 1. Each trial started with the central fixation point. After a varying delay (duration depending on SOA), a prime was displayed for 13 ms at one of four possible locations. Then, a target was presented for 133 ms at the same position as the prime at prime-target SOAs of 27, 40, 53, or 67 ms. Participants had to decide as quickly and accurately as possible whether the target was green or red by pressing a right or left button (reversed for half of the participants) while maintaining fixation. They used the index and middle finger of their dominant hand. In each trial, the prime color was either consistent or inconsistent with the target color and thereby with the required motor response. Also, the target was either presented alone (baseline condition without distractors), or together with one or seven target distractors, whose color was either consistent or inconsistent with the target color and which could appear in three different levels of saturation (Figure 1). Note that at the lowest level of saturation, distractors were of identical gray for red and green targets. The time interval from fixation to target onset was constant at 600 ms.

The 720 trials each participants completed in each task and session are distributed across conditions as follows: the baseline conditions without distractors were presented 120 times per prime-target consistency (15 repetitions x target color (2) x prime-target SOA (4) = 120), adding up to 240 trials. The other conditions were each presented 24 times (3 repetitions x target color (2) x prime-target SOA (4) = 24), adding up to the remaining 480 trials. All 22 conditions within the target distractor task are listed in the lower part of Table A1.

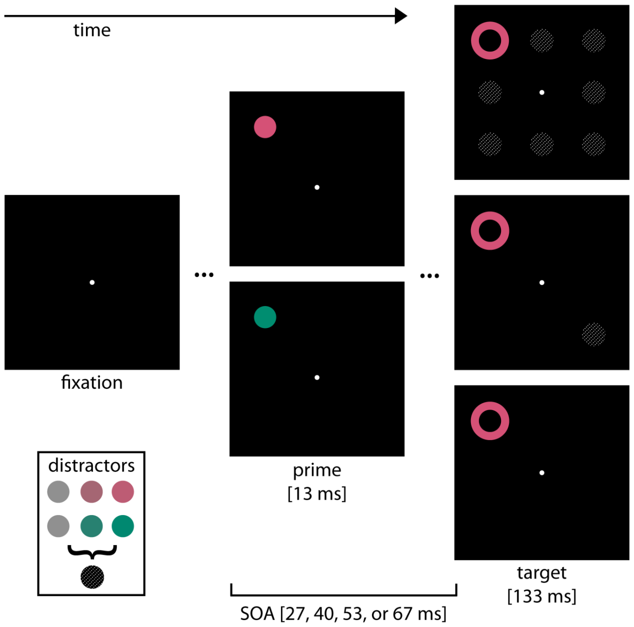

Figure 1. Stimuli and procedure of the target distractor task of Experiment 1. Primes and targets could also be displayed at one of the three other corners of an imaginary square centered on fixation; targets could also be green. See text for further details.

2.2.3.2. Prime distractor task. The experimental procedure was the same as of the target distractor task (cf. Figure 1) except that distractors (prime-consistent, prime-inconsistent, or neutral) were presented simultaneously with the primes rather than with the targets. All 22 conditions within the prime distractor task are listed in the upper part of Table A1.

2.2.4. Data treatment and statistical methods. In both tasks, practice blocks were not analyzed and trials were eliminated if response times were shorter than 100 ms or longer than 1000 ms (an *a priori* criterion eliminating 0.11% and 0.14% of trials in the target distractor task and the prime distractor task, respectively). In the target distractor task, 30 trials were lost due to technical failure. Repeated-measures analyses of variance (ANOVAs) were performed with factors prime-target consistency (*C*), prime-target SOA (*S*), distractors' consistency with the concomitant prime or target (*CD*), number of distractors (*ND*) and saturation of distractors (*SD*). We report Huynh-Feldt-corrected degrees of freedom and *p* values, and *F* values with subscripts indicating the respective effect (e.g., $F_{C\times S}$ for the interaction of prime-target consistency and prime-target SOA) and report effect size η^2 (Levine & Hullett, 2002) in which 0.01 conventionally reflects a small, 0.059 a medium, and 0.138 reflects a large effect (Cohen, 1988). All significant effects are reported. Error trials were not included in the response time analysis but error rates were subjected to separate ANOVAs after they had been arcsine-transformed to comply with ANOVA requirements. Overall error rates were 13.04% and 13.09% of trials in the target and prime distractor tasks, respectively. Finally, we analyzed the time course of priming effects by splitting raw response times (including outliers) into 10 bins (from fastest to slowest responses) for each condition and each participant. Then, we calculated the mean response time for each bin, and built the grand average of these means for response time bins 1 to 9 for each of our experimental conditions (bin 10 is not included because it is likely to be distorted by outliers).

2.3. Results

Overviews of the results for response times for the prime-distractor and target-distractor tasks are given in Figures 2 and 3, respectively (for plots of error rates, see Figures A1 and A2 in the Appendix; exact means are provided in Tables A1 and A2). In both figures (Figures 2 and 3), there are 11 priming effects (consistent and inconsistent trials as a function of SOA), one for each possible combination of distractor presence/absence, number, and saturation. Overall, most of these combinations allow for clear response priming effects that increase with SOA but are strongly modulated by the distractors. For prime distractors (Figure 2), analysis of variance with factors of prime-target consistency (*C*), SOA (*S*), and distractor combinations (*D*, with 11 levels) showed that response times were faster with consistent than with inconsistent primes [$F_C(1,7) = 145.15$, $p < .001$, $\eta^2 = 0.47$] and that this priming effect increased with SOA [$F_{C\times S}(2.88,20.16) = 33.08$, $p < .001$, $\eta^2 = 0.08$]. Responses were generally faster with increasing SOA [$F_S(2.19,15.30) = 9.02$, $p = .002$, $\eta^2 = 0.02$]. There was a main effect of distractor combination [$F_D(3.41,23.85) = 14.73$, $p < .001$, $\eta^2 = 0.17$], and also an interaction effect of this factor and consistency [$F_{C\times D}(2.78,19.46) = 9.74$, $p < .001$, $\eta^2 = 0.19$]. Thus, distractor combination affected response times as well as priming effects with no interactions with prime-target SOA [$F < 0.99$, $p > .50$].

The same ANOVA model for target distractors (Figure 3) also showed that response times were faster with consistent than with inconsistent primes [$F_C(1,7) = 116.41$, $p < .001$, $\eta^2 = 0.56$] as well as an increase of this priming effect with SOA [$F_{C\times S}(2.05,14.35) = 29.18$, $p < .001$, $\eta^2 = 0.09$]. Again, responses were generally faster with increasing SOA [$F_S(2.33,16.34) = 13.36$, $p < .001$, $\eta^2 = 0.03$], and we found a main effect of distractor combination [$F_D(3.76,26.31) = 11.76$, $p < .001$, $\eta^2 = 0.12$] which also modulated priming effects [$F_{C\times D}(3.31,23.19) = 9.28$, $p < .001$, $\eta^2 = 0.09$]. Also, there were no significant interactions with prime-target SOA [$F < 1.73$, $p > .140$].

In the following, we will report analyses to specifically test the three hypotheses developed in the introduction. To keep the analyses reasonably simple, we average across SOA, keeping in mind that this factor modulates the priming effects in most distractor combinations. We break down the data into two components: the priming effect, RT_{incon}-RT_{con}, and the overall response time, *RT* (i.e., responses times averaged across prime-target consistent and inconsistent trials), because prime and target distractors are predicted to affect these two components separately. To simplify the report, our analyses leave out the no-distractor baseline because it breaks the simple two-factorial design of distractor number and distractor saturation, but all results of the no-distractor baseline are plotted in the figures for comparison.

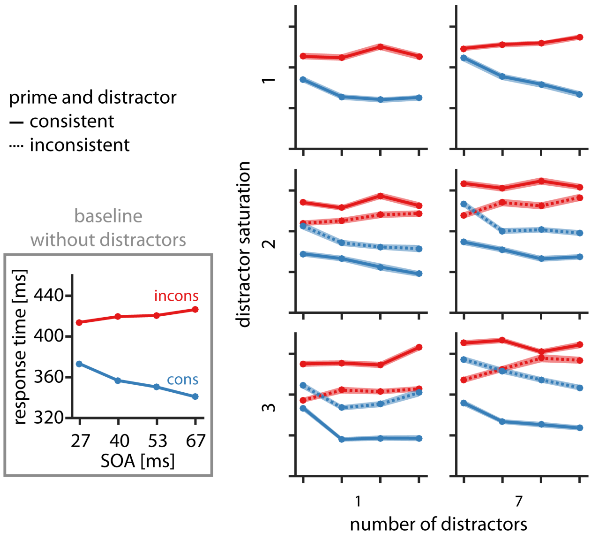

Figure 2. Response times in the prime distractor task in Experiment 1. Left panel: response time as a function of prime-target SOA and prime-target consistency in the baseline condition without distractors. Right panels: Response times in the remaining conditions. Each plot gives response time as a function of SOA and consistency (see left panel for scale and legend). Rows and columns are organized by number of distractors (columns) and distractor saturation (rows). Line color denotes prime-target consistency (consistent: blue, inconsistent: red), line style denotes prime-distractor consistency (prime-consistent: solid, prime-inconsistent: dashed). Note that for gray distractors (distractor saturation = 1), distractor consistency is not defined. Transparent error margins denote standard errors corrected for between-subjects variance (Cousineau, 2005).

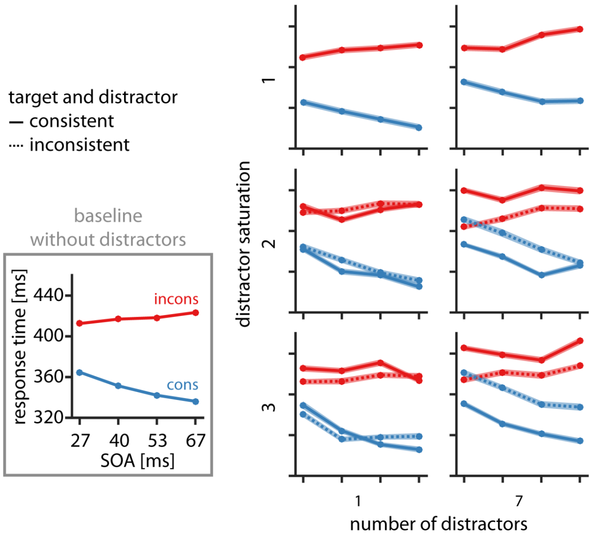

Figure 3. Response time results of the target distractor task in Experiment 1. Details as in Figure 2, except that line-style now denotes target-distractor consistency (target-consistent: solid, target-inconsistent: dashed).

2.3.1. Testing the singleton hypothesis. To test this hypothesis, we analyze priming effects in the prime distractor task separately for prime-consistent and prime-inconsistent distractors (lower row of Figure 4). With prime-consistent distractors, priming effects should decrease with increasing distractor saturation–as the increasing similarity between primes and distractors makes primes stand out less. Conversely, with prime-inconsistent distractors, priming effects should increase with increasing saturation. We calculated two separate ANOVAs for consistent and inconsistent primes and targets, with the single factor of distractor saturation (*SD*), averaged across prime-target SOA and number of distractors, and only for conditions with distractors present (lower row of Figure 4; 1 and 7 distractors). We find that for prime-consistent distractors, priming effects *increase* with saturation of distractors in response times [$F_{\mathrm{C}\times\mathrm{SD}}(1.07,7.47) = 11.20$, $p = .011$, $\eta^2 = 0.14$] (lower left panel in Figure 4) and in error rates [$F_{\mathrm{C}\times\mathrm{SD}}(1.51,10.58) = 4.57$, $p = .045$, $\eta^2 = 0.15$]; and that for prime-inconsistent distractors, priming effects *decrease* with saturation of distractors in response times [$F_{\mathrm{C}\times\mathrm{SD}}(2,14) = 10.19$, $p = .002$, $\eta^2 = 0.09$] (lower right panel in Figure 4) and error rates [$F_{\mathrm{C}\times\mathrm{SD}}(1.35,9.47) = 4.69$, $p = .049$, $\eta^2 = 0.14$]. Note that the no-distractor baseline yields particularly fast responses and large priming effects. This pattern is exactly opposite to what we would expect if the singleton hypothesis were true, and also opposite to the predictions of the perceptual load hypothesis.

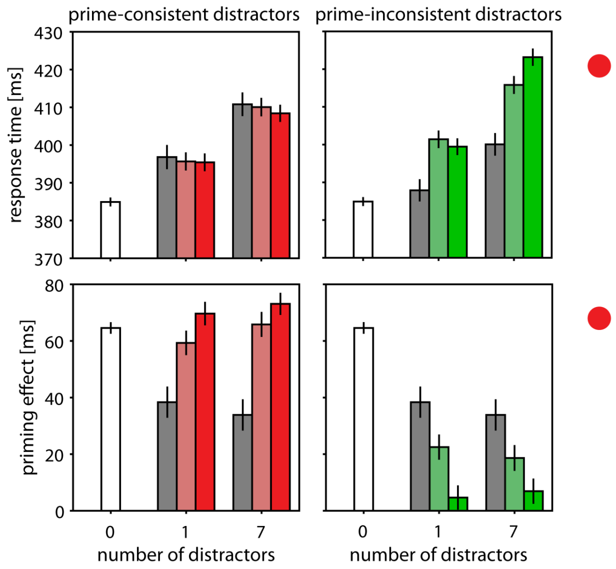

Figure 4. Results of the prime distractor task in Experiment 1. Overall response times (upper panels) and response time priming effects (lower panels) for prime-consistent distractors (left panels) and prime-inconsistent distractors (right panels). Response times were averaged across prime-target consistent and inconsistent trials. Response times as well as priming effects were averaged across prime-target SOAs and are plotted as a function of the number of distractors (0, 1, or 7), separately for the different levels of distractor saturation (different bars). Note that the response times and priming effects of the baseline (white bars), as well as the priming effects for the gray distractors (gray bars) are identical for prime-consistent and prime-inconsistent distractors (left and right panels) and are repeated to facilitate the comparison. The red prime is included for illustration purposes only; color values are different from the actual experiment.

In the target distractor task, also response times and error rates should follow a specific pattern (upper row of Figure 5). With target-consistent distractors, responses should be slower and less accurate with increasing saturation–because targets stand out less. Conversely, with target-inconsistent distractors, responses should be faster and more accurate with increasing saturation. Again, we calculated two separate ANOVAs with the single factor of saturation of distractors (*SD*), averaged across prime-target consistency, prime-target SOA and number of distractors, and only for conditions with distractors present (upper row of Figure 5; 1 and 7 distractors). For target-consistent distractors, there is no effect of distractor saturation on response times [$F_{SD}(1.11,7.78) = 0.30$, $p = .624$, $\eta^2 = 0.00$] (upper left panel in Figure 5) or error rates [$F_{SD}(1.95,13.68) = 0.28$, $p = .754$, $\eta^2 = 0.00$] (Figures 5 and A2). For target-inconsistent distractors, responses are *slower* [$F_{SD}(2,14) = 8.69$, $p = .004$, $\eta^2 = 0.05$] with increasing saturation of distractors (upper right panel in Figure 5); with no effect on error rates [$F_{SD}(1.48,10.33) = 3.55$, $p = .077$, $\eta^2 = 0.05$]. As before, the no-distractor baseline yields particularly fast responses and large priming effects. Again, this pattern is not consistent with either the singleton or the perceptual load hypothesis (Lavie, 1995, 2005, 2009).

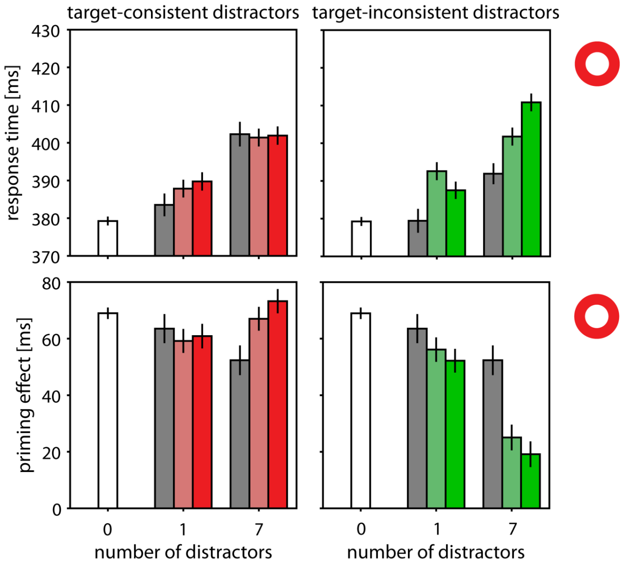

Figure 5. Results of the target distractor task in Experiment 1. Overall response times (upper panels) and response time priming effects (lower panels) for target-consistent distractors (left panels) and target-inconsistent distractors (right panels). For details see Figure 4.

2.3.2. Testing the crowding hypothesis. To test the standard crowding hypothesis, we analyze priming effects in the prime distractor task, only including the baseline and neutral distractors (white and grey bars in the lower row of Figure 4). Specifically, with an increasing number of prime distractors, priming effects should decrease. We calculate an ANOVA with factors of prime-target consistency (*C*) and number of distractors (*ND*), averaged across prime-target SOA. We find main effects of consistency in response times [$F_{C}(1,7) = 235.56$, $p < .001$, $\eta^2 = 0.57$] and error rates [$F_{C}(1,7) = 88.97$, $p < .001$, $\eta^2 = 0.74$], and of number of distractors in response times [$F_{ND}(2,14) = 9.26$, $p = .003$, $\eta^2 = 0.09$]. In line with the hypothesis, priming effects decrease with increasing number of distractors in response times [$F_{C \times ND}(2,14) = 18.81$, $p < .001$, $\eta^2 = 0.08$] and in error rates [$F_{C \times ND}(2,14) = 4.54$, $p = .030$, $\eta^2 = 0.20$]. Note, though that this finding is due to the difference between no distractors vs. presence of distractors: even though crowding should be stronger for an increasing numbers of distractors, there is virtually no difference in priming effects between 1 and 7 distractors (about 1 ms).

In the target distractor task, response times and priming effects should follow a specific pattern as well: As the relative impact of the target should be weaker with more interference, response times should be slower with increasing number of target distractors (white and grey bars in the upper row of Figure 5). Indeed, when calculating an ANOVA with the same factors as for the prime distractor task, we find that neutral target distractors increase the overall response times [$F_{ND}(1.21,8.48) = 15.20$, $p = .003$, $\eta^2 = 0.08$] (Figure 5). However, priming effects [$F_C(1,7) = 128.20$, $p < .001$, $\eta^2 = 0.58$] *decrease* with the number of target distractors in response times [$F_{C \times ND}(1.84,12.89) = 25.44$, $p < .001$, $\eta^2 = 0.02$] (white and grey bars in the lower row of Figure 5)–with no effect on priming effects in error rates [$F_C(1,7) = 62.73$, $p < .001$, $\eta^2 = 0.77$; $F_{C \times ND}(1.80,12.60) = 2.51$, $p = .124$, $\eta^2 = 0.06$] (Figure A2). This decrease in priming is not in line with the crowding hypothesis: If crowding reduced response activation by the targets, this should rather help than hinder the priming effect. Our results are also at odds with extensions of crowding theory that assume that crowding effects are modulated by target-distractor similarity or grouping (e.g., Francis et al., 2017; Manassi et al., 2012; Rosen, Chakravarthi, & Pelli, 2014), because predictions from those accounts are very similar to those of the singleton hypothesis.

2.3.3. Testing the motor access hypothesis. To test this hypothesis, we analyze response times and error rates in the prime distractor task with colored distractors only (red and green bars in Figure 4). Prime distractors that share the color of the primes should add to the priming effect, whereas prime distractors with conflicting color should diminish the priming effect, and this effect should increase with increasing number and saturation of the distractors. We calculated ANOVAs with factors of prime-target consistency (*C*), distractor-prime consistency (*CD*), number of distractors (*ND*), and saturation of distractors (*SD*), averaged across prime-target SOA, and only for conditions with colored distractors (red and green bars in Figure 4).

We find slower and less accurate responses with increasing number and saturation of distractors [response times: $F_{ND}(1,7) = 50.37$, $p < .001$, $\eta^2 = 0.11$; $F_{SD}(1.49,10.40) = 20.77$, $p < .001$, $\eta^2 = 0.03$; error rates: $F_{ND}(1,7) = 6.11$, $p = .043$, $\eta^2 = 0.04$; $F_{SD}(1.41,9.85) = 12.88$, $p = .003$, $\eta^2 = 0.12$] (upper row of Figure 4), and strong priming effects in response times [$F_C(1,7) = 133.73$, $p < .001$, $\eta^2 = 0.44$] (lower row of Figure 4) and error rates [$F_C(1,7) = 60.37$, $p < .001$, $\eta^2 = 0.59$]. These effects are indeed strongest when prime and distractors have the same color (lower left panel in Figure 4), and weaker when they have different colors [response times: $F_{C \times CD}(1,7) = 28.84$, $p = .001$, $\eta^2 = 0.13$; error rates: $F_{C \times CD}(1,7) = 24.69$, $p = .002$, $\eta^2 = 0.22$] (lower right panel in Figure 4). This impact of the distractors on the priming effect does not depend on the number of distractors, neither in response times [$F_{C \times CD \times ND}(1,7) = 1.00$, $p = .352$, $\eta^2 = 0.00$] nor in error rates [$F_{C \times CD \times ND}(1,7) = 0.25$, $p = .632$, $\eta^2 = 0.00$]. However, it is modulated by distractor saturation, such that priming effects with prime-consistent distractors slightly increase with distractor saturation, and priming effects with prime-inconsistent distractors decrease with distractor saturation in response times [$F_{C \times CD \times SD}(1.31,9.19) = 12.15$, $p = .005$, $\eta^2 = 0.10$] (lower left and right panels in Figure 4) and error rates [$F_{C \times CD \times SD}(1.65,11.57) = 6.17$, $p = .018$, $\eta^2 = 0.14$]. All other effects were non-significant.

Additionally, we can test the motor access hypothesis by analyzing response times and error rates in the target distractor task. Target distractors that share the color of the targets should speed responses, whereas target distractors with conflicting color should slow them. We calculate the same ANVOAs as for the prime distractor task (red and green bars in Figure 5). Again, we find slower responses with increasing number and saturation of distractors [response times: $F_{ND}(1,7) = 41.94$, $p < .001$, $\eta^2 = 0.09$; $F_{SD}(2,14) = 11.14$, $p = .001$, $\eta^2 = 0.02$] (upper row of Figure 5), and strong priming effects in response times [$F_{C}(1,7) = 109.85$, $p < .001$, $\eta^2 = 0.54$] (lower row of Figure 5) and error rates [$F_{C}(1,7) = 37.01$, $p < .001$, $\eta^2 = 0.67$]. These priming effects are reduced by increasing distractor number and saturation [response times: $F_{C\times ND}(1,7) = 12.48$, $p = .010$, $\eta^2 = 0.01$; $F_{C\times SD}(1.52,10.63) = 5.72$, $p = .026$, $\eta^2 = 0.00$; error rates: $F_{C\times ND}(1,7) = 13.26$, $p = .008$, $\eta^2 = 0.06$; $F_{C\times SD}(2,14) = 9.14$, $p = .003$, $\eta^2 = 0.06$]. Priming effects are also smaller for inconsistent distractors [response times: $F_{C\times CD}(1,7) = 15.70$, $p = .005$, $\eta^2 = 0.04$; error rates: $F_{C\times CD}(1,7) = 59.74$, $p < .001$, $\eta^2 = 0.20$], an effect that is more pronounced with increasing distractor number and saturation [response times: $F_{C\times CD\times ND}(1,7) = 13.53$, $p = .008$, $\eta^2 = 0.02$; $F_{C\times CD\times SD}(1.32,9.24) = 5.09$, $p = .043$, $\eta^2 = 0.01$; $F_{C\times CD\times ND\times SD}(1.77,12.44) = 7.30$, $p = .009$, $\eta^2 = 0.01$; error rates: $F_{C\times CD\times ND}(1,7) = 15.63$, $p = .006$, $\eta^2 = 0.08$; $F_{C\times CD\times SD}(1.52,10.67) = 9.31$, $p = .007$, $\eta^2 = 0.12$] (lower right panel in Figure 5). However, we find that neither response times nor error rates were different for trials where targets and distractors had the same color versus different colors [response times: $F_{CD}(1,7) = 2.27$, $p = .176$, $\eta^2 = 0.00$; error rates: $F_{CD}(1,7) = 0.98$, $p = .356$, $\eta^2 = 0.01$] (lower left and right panels in Figure 5). All other effects were non-significant.

2.1. Discussion

Results from Experiment 1 are generally inconsistent with the singleton hypotheses and the perceptual load hypotheses, and they are also at odds with the crowding hypothesis. None of those theories is able to explain the data on its own. However, our results lend support to the motor access account, which states that distractors simply contribute to the response activation process as would be expected from additional (and potentially conflicting) primes or flankers.

Still, our experiment has a number of limitations.[1] First, we cannot rule out that metacontrast masking of primes by targets contributed to the findings. Even though response priming has repeatedly been found to be independent of the amount and time-course of metacontrast masking (e.g., Vorberg et al., 2003; Albrecht, Klapötke, & Mattler, 2010), other forms of masking have been found to interfere with response priming (F. Schmidt, Haberkamp, & T. Schmidt, 2011), and we cannot be certain that our results have not been complicated by masking effects. Second, as prime and target always appeared at the same position, participants were able to predict the position of the upcoming target from the position of the prime, which could boost target processing and lead to attentional suppression of distractor positions. Third, the fact that primes and targets had different shapes might have reduced the impact of the primes. Finally, we cannot exclude that singleton or crowding effects do take place in addition to response activation and diminish its effect.

3. Experiment 2

3.1. General

To respond to the limitations of Experiment 1, we presented primes, targets and distractors at different positions on an imaginary circle around fixation, and used the same annulus shape for primes and targets. This arrangement precludes metacontrast masking of primes by targets, as well as prediction of target position from prime position. To reduce the number of conditions, we used a single prime-target SOA of 67 ms and two different numbers of distractors (0 vs. 6).

3.2. Methods

3.2.1. Participants. Eight students from the University of Kaiserslautern, Germany

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[1] We thank an anonymous reviewer for detailing the following argument.

(age 25-37 years, three of them male, three of them left-handed) with normal or corrected vision participated in the experiment for financial compensation (6 €/h). Participants were treated as in Experiment 1.

3.2.2. Apparatus and Stimuli. In contrast to Experiment 1, both primes and targets were annuli with an outer diameter of 1.13° and an inner diameter of 0.71° of visual angle. Primes were presented at one of 18 regular-spaced positions along an imaginary circle with a diameter of 3.40 cm (3.90° of visual angle), centered on fixation. Targets were presented also at one of these positions but never at the same position as the primes. Distractors were disks with a diameter of 0.71° of visual angle and were presented at six of the 18 positions. Distractors could not appear at a position occupied by either a prime or target. Prime, target, and distractor positions were chosen randomly. All other details of apparatus and stimuli were the same as in Experiment 1.

3.2.3. Procedure. Each participant performed two 30-minute sessions of a response priming task. In each session, they responded to 1,008 experimental trials of either the prime distractor or the target distractor task, respectively, adding up to 2,160 trials per participant. The order of both tasks was counterbalanced across sessions and participants. Sessions were organized into a practice block followed by 48 experimental blocks of 21 trials each. After each block, we provided participants with summary feedback on their response times and error rates.

3.2.3.1.Target distractor task. The experimental procedure is similar to that illustrated in Figure 1. Each trial started with the central fixation point. After a delay, a prime was displayed for 13 ms at one of 18 possible locations. Then, a target was presented for 133 ms at a randomly selected position different from of the prime at a prime-target SOA of 67 ms. As primes and targets had the same shape, participants were instructed to respond to the stimuli appearing at the end of each trial while maintaining fixation. Specifically, they had to decide as quickly and accurately as possible whether the target was green or red by pressing a right or left button (reversed for half of the participants). In each trial, the prime color was either consistent or inconsistent with the target color and thereby with the required motor response. Also, the target was either presented alone (baseline condition without distractors), or together with six distractors, whose color was either consistent or inconsistent with the target color and which could appear at three different levels of saturation (cf. Figure 1). Note that at the lowest level of saturation, distractors were of identical gray for red and green targets. The time interval from fixation to target onset was constant at 600 ms.

Because for no distractors, distractor color and saturation did not apply and because distractors at the lowest level of saturation were identical, we presented a total of 24 out of the 48 possible combinations of target color (2), prime-target consistency (2), target-distractor consistency (2), number of distractors (2), and distractor saturation (3) equiprobably and pseudo-randomly (see Table A3 for a list of those combinations for each task–without target color as it was not considered in the statistical analyses). Consequently, each combination was presented 42 times to each participant in each task.

3.2.3.2. Prime distractor task. The experimental procedure was the same as of the target distractor task except that distractors (prime-consistent, prime-inconsistent, or neutral) were presented simultaneously with the primes instead of the targets.

3.2.4. Data treatment and statistical methods. Data treatment and statistical methods were the same as in Experiment 1. The outlier criterion eliminated 2.2% and 0.8% of response times in the target and prime distractor tasks, respectively. Overall error rates were 13.69% and 12.70% of trials in the target and prime distractor tasks, respectively. All significant effects are reported.

Table A3. Mean response time (*RT*) and standard deviation (*SD RT*) in Experiment 2.

Affected event	Prime target consistency	Color of distractor	No of distractors	Saturation of distractors	RT [ms]	SD RT [ms]
Prime	cons		0		452.48	117.52
		grey	6	1	470.06	110.25
		same color	6	2	447.89	111.03
				3	437.44	102.19
		other color	6	2	487.93	103.10
				3	493.33	109.93
	incons		0		535.44	108.67
		grey	6	1	540.40	107.22
		same color	6	2	527.86	109.92
				3	529.82	109.75
		other color	6	2	544.76	115.83
				3	540.87	116.62
Target	cons		0		464.86	120.05
		grey	6	1	495.01	117.00
		same color	6	2	473.14	120.94
				3	474.60	109.14
		other color	6	2	524.81	131.54
				3	531.01	130.37
	incons		0		556.54	126.32
		grey	6	1	576.49	134.11
		same color	6	2	572.69	120.04
				3	573.95	126.75
		other color	6	2	573.91	135.27

3.3. Results

Overviews of the results for response times for the prime-distractor task and target-distractor task are given in Figures 6 and 7, respectively (Tables A3 and A4 in the Appendix provide mean response times and error rates per condition). In the following, we will report analyses to specifically test the three hypotheses developed in the introduction and to test whether we replicate the findings of Experiment 1.

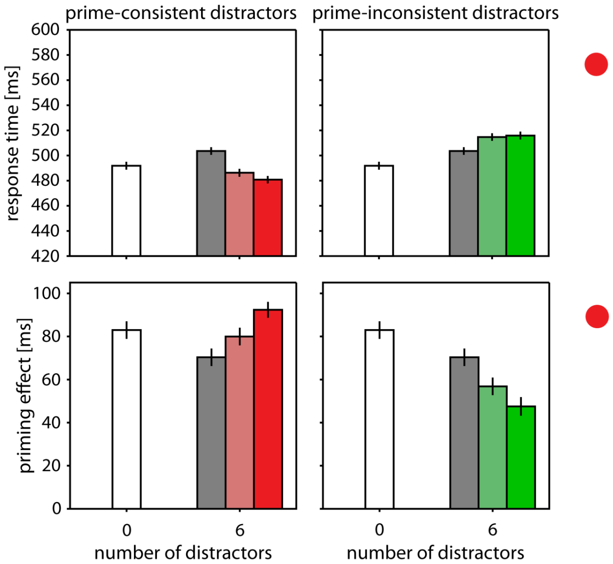

Figure 6. Results of the prime distractor task in Experiment 2. Overall response times (upper panels) and response time priming effects (lower panels) for prime-consistent distractors (left panels) and prime-inconsistent distractors (right panels). Response times were averaged across prime-target consistent and inconsistent trials. Response times as well as priming effects are plotted as a function of the number of distractors (0 or 6), separately for the different levels of distractor saturation (different bars). Note that the response times and priming effects of the baseline (white bars), as well as the priming effects for the gray distractors (gray bars) are identical for prime-consistent and prime-inconsistent distractors (left and right panels) and are repeated to facilitate the comparison. The red prime is included for illustration purposes only; color values are different from the actual experiment.

3.3.1. Testing the singleton hypothesis. Equivalently to Experiment 1, we analyzed priming effects in the prime distractor task separately for prime-consistent and prime-inconsistent distractors (lower row of Figure 6). We calculated two separate ANOVAs with factors of prime-target consistency (*C*) and saturation of distractors (*SD*), only for conditions with distractors present (lower row of Figure 6; 6 distractors). For prime-consistent distractors, we find faster responses with increasing saturation of distractors [$F_{SD}(1.57,10.98) = 15.44$, $p = .001$, $\eta^2 = 0.03$]. Also, we find strong priming effects [response times: $F_C(1,7) = 41.32$, $p < .001$, $\eta^2 = 0.33$; error rates: $F_C(1,7) = 34.33$, $p = .001$, $\eta^2 = 0.39$] that *increase* with saturation of distractors in response times [$F_{C\times SD}(1.66,11.64) = 4.53$, $p = .040$, $\eta^2 = 0.01$] (lower left panel in Figure 6) but not in error rates [$F_{C\times SD}(2,14) = 2.55$, $p = .114$, $\eta^2 = 0.02$].

For prime-inconsistent distractors, responses are slower with increasing distractor saturation [$F_{SD}(2,14) = 5.53$, $p = .017$, $\eta^2 = 0.01$] while priming effects [response times: $F_C(1,7) = 14.54$, $p = .007$, $\eta^2 = 0.20$; error rates: $F_C(1,7) = 60.56$, $p < .001$, $\eta^2 = 0.44$] *decrease* with saturation of distractors in response times [$F_{C\times SD}(1.92,13.41) = 4.09$, $p = .040$, $\eta^2 = 0.01$] (lower right panel in Figure 6) but not in error rates [$F_{C\times SD}(1.46,10.23) = 0.19$, $p = .762$, $\eta^2 = 0.01$]. Like in Experiment 1, the no-distractor baseline yields particularly fast responses and large priming effects. The pattern in response times is replicating Experiment 1 and is exactly opposite to what we would expect if the singleton hypothesis were true, and also opposite to the predictions of the perceptual load hypothesis.

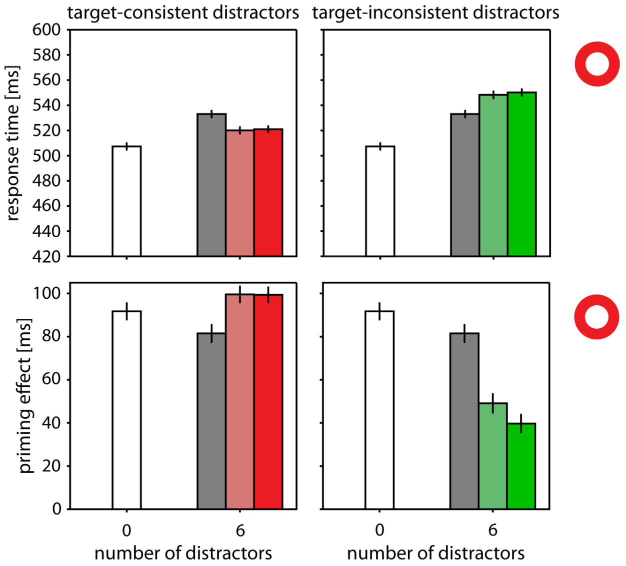

Figure 7. Results of the target distractor task in Experiment 2. Overall response times (upper panels) and response time priming effects (lower panels) for target-consistent distractors (left panels) and target-inconsistent distractors (right panels). For details see Figure 6.

In the target distractor task, we again calculated two separate ANOVAs with factors of prime-target consistency (*C*) and saturation of distractors (*SD*), only for conditions with distractors present (upper row of Figure 7; 6

distractors). For target-consistent distractors, responses are slightly *faster* with increasing saturation of distractors [$F_{SD}(1.92,13.43) = 5.06$, $p = .024$, $\eta^2 = 0.00$]; with no effect on error rates [$F_{SD}(2,14) = 0.91$, $p = .427$, $\eta^2 = 0.01$]. Priming effects in response times [$F_{C}(1,7) = 54.04$, $p < .001$, $\eta^2 = 0.27$] (lower left panel in Figure 7) and error rates [$F_{C}(1,7) = 13.75$, $p = .008$, $\eta^2 = 0.35$] were not affected by distractor saturation [both $F_{C\times SD} < 2.40$, p > .133]. For target-inconsistent distractors, responses are *slower* and *less accurate* with increasing saturation of distractors [response times: $F_{SD}(2,14) = 20.25$, $p < .001$, $\eta^2 = 0.01$; error rates: $F_{SD}(2,14) = 6.01$, $p = .013$, $\eta^2 = 0.06$]. Priming effects in response times [$F_{C}(1,7) = 19.62$, $p = .003$, $\eta^2 = 0.11$] decreased with increasing distractor saturation [$F_{C\times SD}(2,14) = 8.03$, $p = .005$, $\eta^2 = 0.02$] (lower right panel in Figure 7), whereas there were no priming effects in error rates. As before, the no-distractor baseline yielded particularly fast responses and large priming effects. Again, this pattern is not consistent with the singleton or perceptual load hypotheses.

3.3.2. Testing the crowding hypothesis. Like in Experiment 1, we analyze priming effects in the prime distractor task, only including the baseline and neutral distractors (white and grey bars in the lower row of Figure 6). We calculated an ANOVA with factors of prime-target consistency (*C*) and number of distractors (*ND*). Priming effects by trend decrease with increasing number of distractors in response times [$F_{C}(1,7) =22.99$, $p = .002$, $\eta^2 = 0.27$; $F_{C\times ND}(1,7) =5.42$, $p = .053$, $\eta^2 = 0.00$] but not in error rates [$F_{C}(1,7) =18.26$, $p = .004$, $\eta^2 = 0.33$; $F_{C\times ND}(1,7) = 0.40$, $p = .546$, $\eta^2 = 0.01$]. In the target distractor task, an ANOVA of the same design shows that neutral target distractors increase the overall response times [$F_{ND}(1,7) = 67.09$, $p < .001$, $\eta^2 = 0.03$] (white and grey bars in the upper row of Figure 7). Both effects are in line with the standard crowding hypothesis. Response time priming effects [$F_{C}(1,7) = 32.03$, $p = .001$, $\eta^2 = 0.24$] by trend decrease with the number of distractors in response times [$F_{C\times ND}(1,7) = 4.73$, $p = .066$, $\eta^2 = 0.00$] (white and grey bars in the lower row of Figure 7)–with no effect of distractors on error rates or priming effects in error rates [$F_{ND}(1,7) = 0.06$, $p = .810$, $\eta^2 = 0.00$; $F_{C}(1,7) = 12.89$, $p = .043$, $\eta^2 = 0.00$; $F_{C\times ND}(1,7) = 0.42$, $p = .536$, $\eta^2 = 0.00$]. Like in Experiment 1, a decrease in priming is not in line with the crowding hypothesis, because crowding should reduce response activation by the target and thus boost the priming effect. Our results are also at odds with models assuming that crowding effects are modulated by target-distractor similarity or grouping, because their predictions are similar to the singleton hypothesis.

3.3.3. Testing the motor access hypothesis. We analyzed response times and error rates in the prime distractor task the same way as in Experiment 1. We calculated an ANOVA with factors of prime-target consistency (*C*), distractor-prime consistency (*CD*), and saturation of distractors (*SD*), and only conditions with colored distractors (red and green bars in Figure 6).

We find strong priming effects in response times [$F_{C}(1,7) = 25.92$, $p = .001$, $\eta^2 = 0.17$] (lower row of Figure 6) and error rates [$F_{C}(1,7) = 47.35$, $p < .001$, $\eta^2 = 0.47$]. In response times, these are indeed strongest when prime and distractors have the same color (lower left panel in Figure 6), and weaker when they have different colors [response times: $F_{C\times CD}(1,7) = 16.03$, $p = .005$, $\eta^2 = 0.01$] (lower right panel in Figure 6). Also, responses are faster and more accurate for consistent distractors [$F_{CD}(1,7) = 36.40$, $p = .001$, $\eta^2 = 0.03$; error rates: $F_{CD}(1,7) = 18.73$, $p = .003$, $\eta^2 = 0.15$], an effect that is more pronounced with higher saturation of distractors [$F_{CD\times SD}(2,14) = 17.38$, $p < .001$, $\eta^2 = 0.02$; $F_{CD\times SD}(2,14) = 5.04$, $p = .022$, $\eta^2 = 0.08$] (upper left and right panels in Figure 6). The impact of distractors on the priming effect is modulated by distractor saturation, such that priming effects with prime-inconsistent distractors decrease with distractor saturation, and priming effects with prime-consistent distractors increase with distractor saturation in response times [$F_{C\times CD\times SD}(1.95,13.64) = 11.32$, $p = .001$, $\eta^2 = 0.01$] (lower left and right panels in Figure 6) but not in error rates [$F_{C\times CD\times SD}(1.38,9.7) = 1.44$, $p = .273$, $\eta^2 = 0.01$]. Finally, responses were somewhat more accurate when distractor saturation was low compared to high or gray distractors [$F_{\mathrm{SD}}(2,14) = 6.66$, $p = .009$, $\eta^2 = 0.05$]. All other effects were non-significant. These findings replicate those of Experiment 1 and are in support of the motor access hypothesis.

For the target distractor task, we calculated the same ANVOA as for the prime distractor task (red and green bars in Figure 7). Again, we find strong priming effects in response times [$F_{\mathrm{C}}(1,7) = 37.32$, $p < .001$, $\eta^2 = 0.19$] (lower row of Figure 7) and error rates [$F_{\mathrm{C}}(1,7) = 8.67$, $p = .022$, $\eta^2 = 0.30$]. In response times, these priming effects are smaller for inconsistent distractors [$F_{\mathrm{C}\times\mathrm{CD}}(1,7) = 45.31$, $p < .005$, $\eta^2 = 0.02$], an effect that is more pronounced with increasing distractor saturation [response times: $F_{\mathrm{C}\times\mathrm{CD}\times\mathrm{SD}}(1.70,11.91) = 16.87$, $p < .001$, $\eta^2 = 0.01$] (lower left and right panels in Figure 7). In contrast to Experiment 1, we now find that response times are faster and more accurate in trials where targets and distractors had the same color versus different colors [response times: $F_{\mathrm{CD}}(1,7) = 48.63$, $p < .001$, $\eta^2 = 0.01$; error rates: $F_{\mathrm{CD}}(1,7) = 7.32$, $p = .030$, $\eta^2 = 0.03$], an effect that is more pronounced with increasing distractor saturation [response times: $F_{\mathrm{CD}\times\mathrm{SD}}(2,14) = 19.44$, $p < .001$, $\eta^2 = 0.01$; error rates: $F_{\mathrm{CD}}(2,14) = 6.27$, $p = .011$, $\eta^2 = 0.03$] (upper left and right panels in Figure 7). This finding is in line with the motor access hypothesis; however, note that it was not observed in Experiment 1. All other effects were non-significant.

4. General Discussion

In the introduction, we discussed the ways in which distractors could modulate the effects of primes and targets based on three hypotheses: (1) singleton, (2) interference, and (3) motor access. Table 1 presents an overview of the main hypotheses and predictions as well as the results from Experiments 1 and 2. In our predictions, we employ the logic that distractors might modulate response activation by the prime and target, such that stronger activation from the prime leads to larger priming effects while stronger activation from the target leads to faster responses overall.

The *singleton hypothesis* predicts that a prime appearing amongst differently colored distractors should be more salient and thus generate a larger priming effect, compared to a prime appearing against same-colored distractors. Likewise, targets appearing among differently colored distractors should

Table 1. Overview of main hypotheses, predictions, and results from Experiments 1 and 2. Cells show predictions for response-time priming effects (larger priming effects: PE+; smaller priming effects: PE–) and overall response times (faster responses: FAST; slower responses: SLOW) for each of the different hypotheses (no specific predictions: ×). Green color denotes effects in line with the predictions, red effects not in line with the predictions, and black denotes no effects. Effects marked with an asterisk were only present in Experiment 2. Note that for the sake of clarity, we did not include all conditions (e.g., the number of distractors).

Experimental conditions		Hypotheses and predictions				
Affected event	Color of distractor	Singleton	Standard crowding	Grouping crowding	Perceptual load	Motor access
Prime	grey	×	PE–	×	×	×
	same color (cons)	PE–	×	PE–	PE–	PE+
	other color (incons)	PE+	×	PE+	PE+	PE–
Target	grey	×	SLOW	×	×	×
	same color (cons)	SLOW*	×	SLOW	×	FAST*
	other color (incons)	FAST	×	FAST	×	SLOW*

allow for faster responses. The opposite is the case in our data: Priming effects are increased, not reduced, when prime distractors appear in the same color as the primes, and response times are increased when targets appear among differently colored distractors. These findings let us conclude that the singleton hypothesis cannot explain the data.

The *crowding hypothesis* makes straightforward predictions only for the case that distractors are neutral in color. It states that neutral distractors during prime presentation should diminish the impact of the primes, and neutral distractors during target presentation should diminish the influence of the targets: specifically, neutral prime distractors should lead to smaller priming effects, and neutral target distractors should lead to higher overall response times, especially when the number of distractors is large. Our data largely support this effect: Neutral prime distractors reduce the priming effect by up to 30 ms, and neutral target distractors increase overall response times by up to 20 ms when compared to conditions without distractors. However, the finding that colored distractors have an effect beyond that of neutral distractors implies that the mere presence and number of distractors does not explain their effects, but that the stimulus-response mapping of the colors must be considered as well. However, theories proposing that crowding is modulated by grouping (e.g., by similarity; Francis et al., 2017; Manassi et al., 2012; Rosen et al., 2014) all make predictions similar to the singleton hypothesis we already rejected. The same is true for perceptual load theory (Lavie, 1995, 2005, 2009). In sum, even though our data support interference theories' predictions for neutral distractors, they do not support predictions for colored distractors.

The *motor access hypothesis* predicts that distractors gain access to the motor response much like primes or targets do. Therefore, prime distractors that share the color of the primes should add to the priming effect, whereas prime distractors whose color conflicts with the prime should diminish the priming effect. Likewise, target distractors that share the target's color should speed responses whereas target distractors with conflicting color should slow them. Our data support the predictions for prime distractors: The higher the saturation of the distractors, the stronger the amplification of priming effects by distractors that share the color of the primes, and the stronger the diminution of priming effects by distractors whose color conflicts with that of the primes. The effect of target-distractor congruency on overall response time was not observed in Experiment 1, but appeared in Experiment 2: target-consistent distractors decreased and target-inconsistent distractors increased response times. This effect would be expected from flanker paradigms (Eriksen & Eriksen, 1974), and Schwarz and Mecklinger (1995) have shown that it increases with flanker-target SOA just as the response priming effect does.

All the effects described so far are consistent with the notion that distractors simply enter the response activation process. The impact of distractors during prime presentation can thus easily be described by standard models of response priming (e.g., Mattler & Palmer, 2012; Schubert et al., 2013; Vorberg et al., 2003). Our own model, *rapid-chase theory* (T. Schmidt et al., 2011), assumes that as soon as a fixed stimulus-response mapping is established under task instructions, the color of a stimulus automatically elicits the assigned motor response (*direct parameter specification*; Neumann, 1990). Distractors as well as primes and targets thus become *action triggers* (Kunde et al., 2003) which access the motor response during their first sweep of visuomotor feedforward processing (Lamme & Roelfsema, 2000; T. Schmidt, Niehaus, & Nagel, 2006; T. Schmidt & F. Schmidt, 2009). If primes and distractors both contribute to response activation, the result would be a mixture of feedforward response activations by primes and distractors, such that the effect of the prime is amplified by prime-consistent and diminished by prime-inconsistent distractors, with higher impact by highly saturated and more numerous distractors. In the context of such a model, the effect of neutral distractors would have to be explained separately, for example, by assuming that neutral stimuli add noise to the response activation process, or tend to activate both responses alike, which both should lead to slower response activation when the target finally appears.

Evidence that response priming is explained by a sequence of feedforward sweeps in response activation comes from studies of pointing movements (e.g., T. Schmidt, 2002; T. Schmidt, Niehaus, & Nagel, 2006; T. Schmidt & F. Schmidt, 2009; cf. Flannigan et al., 2016), lateralized readiness potentials (Vath & T. Schmidt, 2004), force profiles in keypress responses (F. Schmidt, Weber, & T. Schmidt, 2014), and analysis of response time distributions (Panis & T. Schmidt, 2016). These studies all show that the timing and direction of the earliest measurable responses exclusively depend on the timing and identity of the prime, but are independent of all properties of the target. This is a strong prediction from rapid-chase theory. Another strong prediction of the theory can be directly evaluated in the present data: When plotting priming effects as a function of responses time (Figure A3), we see that priming effects in most conditions are fully present in the fastest motor responses, an indicator of sequential feedforward processing of primes and target (T. Schmidt et al., 2011; F. Schmidt & Vancleef, 2016). The only exceptions to this pattern are conditions with seven inconsistent prime distractors (Exp. 1), where priming effects are only present in slower responses. Here, we would conclude that feedforward activation by prime and distractors cancel each other, and that the priming effects still observed do not stem from a feedforward process but from later recurrent activation (F. Schmidt & Vancleef, 2016).

The impact of distractors during target presentation is more complex. If target distractors would simply activate their associated responses, then distractors consistent with the target should enhance response activation by the target, and distractors inconsistent with the target should interfere with it. As a result, target-consistent distractors should lead to faster responses, and target-inconsistent distractors to slower responses (flanker effect, Eriksen & Eriksen, 1974). This effect is indeed observed in Experiment 2, but not in Experiment 1. What's more problematic is that inconsistent target distractors should reduce priming effects and that consistent distractors should increase priming effects: stronger targets should be more effective in overcoming response activation by the prime and thus reduce the priming effect. However, our data show the opposite pattern: inconsistent distractors *reduce* priming effects in both experiments. This reduction is accompanied by an overall slowing of responses, and it increases with distractor saturation. Can this finding be reconciled with the motor access hypothesis?

An important clue is that this reduction in priming effects and overall response slowing with stronger targets occurs selectively in the slowest responses, whereas the priming effect is fully intact in the fastest responses (Figure A4). This phenomenon has been observed previously and has been explained by selective inhibition of the primed response (Jaśkowski & Przekoracka-Krawczyk, 2005) that is initiated late in the trial (Ocampo & Finkbeiner, 2013) and that is even able to reverse the sign of the priming effect (leading to the so-called *negative compatibility effect*; e.g., Eimer & Schlaghecken, 2002). T. Schmidt, Hauch, and F. Schmidt (2015) show that primed pointing movements are subject to a counterforce that is applied late in the trial in exact counterdirection to the primed response. Panis and T. Schmidt (2016) illustrate the same process by analyzing the hazard functions of the response time distributions. If inhibition of the primed response is at work in our data, it remains an open question why its effect increases with color saturation of the target distractors. Maybe the inhibition is initiated under cognitive control in response to conflicting target signals and is more vigorous when the conflict is more salient.

In sum, we suggest that most of the effects observed here can be explained by a simple feedforward model, which assumes that prime and target distractors simply contribute to the effects of the primes and targets and thus either enhance or counteract their influence. The eventual priming effect would thus result from a mixture of possibly conflicting response activations by primes, distractors, and targets. On top of this feedforward activation process are attempts to bring the response under cognitive control by inhibiting the primed response, especially in situations where target-inconsistent distractors are especially salient. This illustrates the different roles of irrelevant objects in tasks in which we are prepared to respond quickly and automatically to features of relevant objects, depending on the characteristics of these distractors but also depending on the phase at which they enter visual processing. Whereas fast responses are exclusively governed by feedforward response activation, slow responses are additionally influenced by cognitive control.

Acknowledgments

Thanks to Jennifer Prodan for data collection and to Brenda Ocampo, Steven Haase, and three anonymous reviewer for helpful comments and suggestions on an earlier version of the manuscript.

Compliance with Ethical Standards

The authors declare that they have no conflict of interest. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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A. Appendix

Table A1. Mean response time (*RT*) and standard deviation (*SD RT*) in Experiment 1.

Affected event	Prime target consistency	Color of distractor	No of distractors	Saturation of distractors	RT [ms]	SD RT [ms]
Prime	cons		0		355	78
		grey	1	1	374	76
		grey	7	1	389	74
		same color	1	2	369	81
				3	364	73
		same color	7	2	380	75
				3	376	72
		other color	1	2	390	85
				3	397	82
		other color	7	2	407	75
				3	420	75
	incons		0		413	74
		grey	1	1	423	79
		grey	7	1	428	73
		same color	1	2	434	73
				3	446	80
		same color	7	2	449	69
				3	413	77
		other color	1	2	402	72
				3	425	86
		other color	7	2	427	83
				3	413	74
Target	cons		0		349	73
		grey	1	1	353	75
		grey	7	1	373	71
		same color	1	2	361	79
				3	363	83
		same color	7	2	371	71
				3	369	76
		other color	1	2	367	83
				3	363	76
		other color	7	2	390	88
				3	401	83
	incons		0		418	74
		grey	1	1	416	67
		grey	7	1	425	72
		same color	1	2	420	73
				3	423	72
		same color	7	2	438	78
				3	443	74
		other color	1	2	423	76
				3	415	71
		other color	7	2	415	75
				3	420	79

Table A2. Mean error rate (*ER*) in Experiment 1.

Affected event	Prime target consistency	Color of distractor	No of distractors	Saturation of distractors	ER [%]
Prime	cons		0		4.2
		grey	1	1	5.8
		grey	7	1	7.5
		same color	1	2	6.6
				3	4.9
		same color	7	2	7.8
				3	5.4
		other color	1	2	10.6
				3	11.3
		other color	7	2	15.1
				3	14.0
	incons		0		19.8
		grey	1	1	17.5
		grey	7	1	15.1
		same color	1	2	20.9
				3	23.0
		same color	7	2	21.2
				3	22.8
		other color	1	2	13.0
				3	13.0
		other color	7	2	17.6
				3	19.8
Target	cons		0		4.2
		grey	1	1	5.0
		grey	7	1	3.7
		same color	1	2	4.6
				3	3.9
		same color	7	2	4.8
				3	4.0
		other color	1	2	5.4
				3	6.0
		other color	7	2	10.4
				3	13.5
	incons		0		23.6
		grey	1	1	20.6
		grey	7	1	19.3
		same color	1	2	21.8
				3	22.8
		same color	7	2	20.7
				3	23.1
		other color	1	2	17.8
				3	17.8
		other color	7	2	14.5
				3	12.7

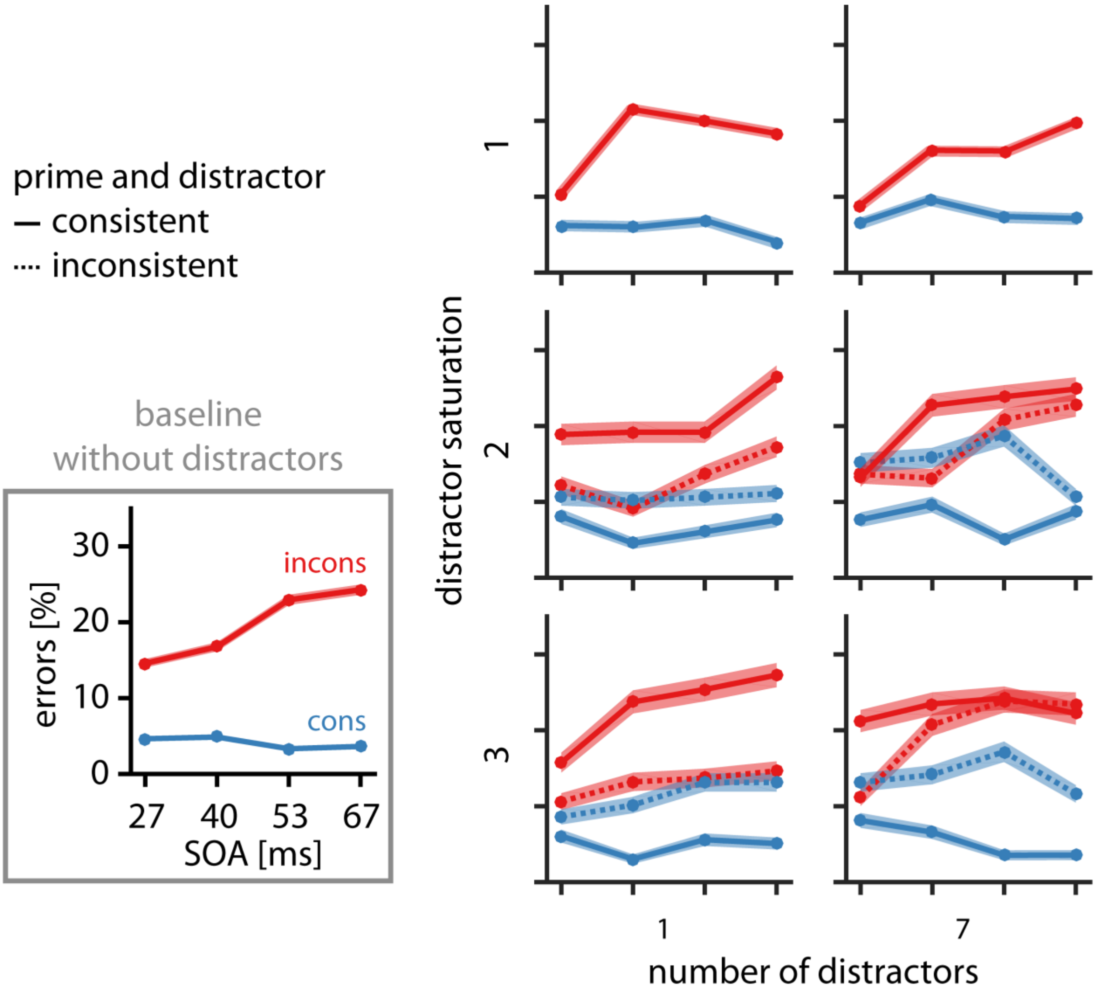

Figure A1. Error rates of the prime distractor task in Experiment 1. For details see Figure 2

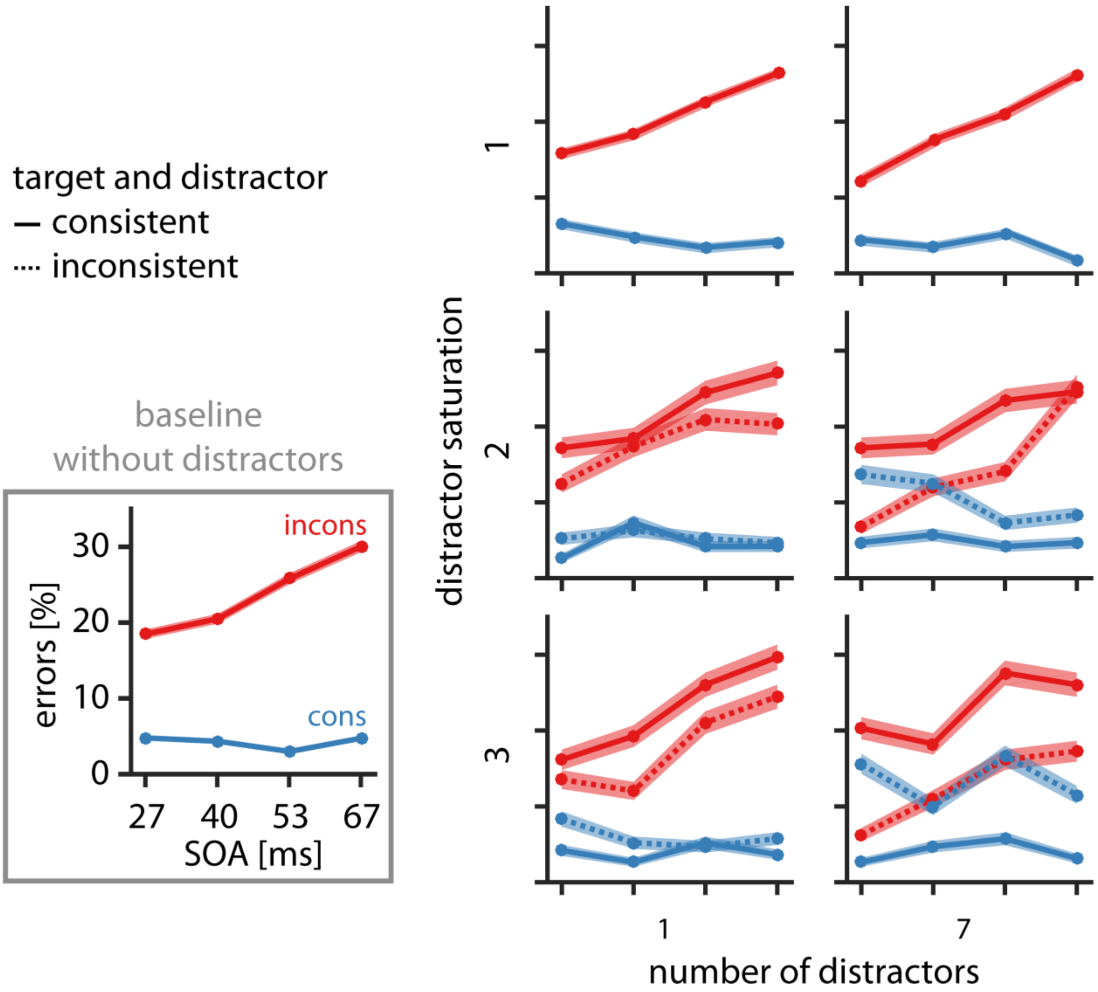

Figure A2. Error rates of the target distractor task in Experiment 1. For details see Figure 2.

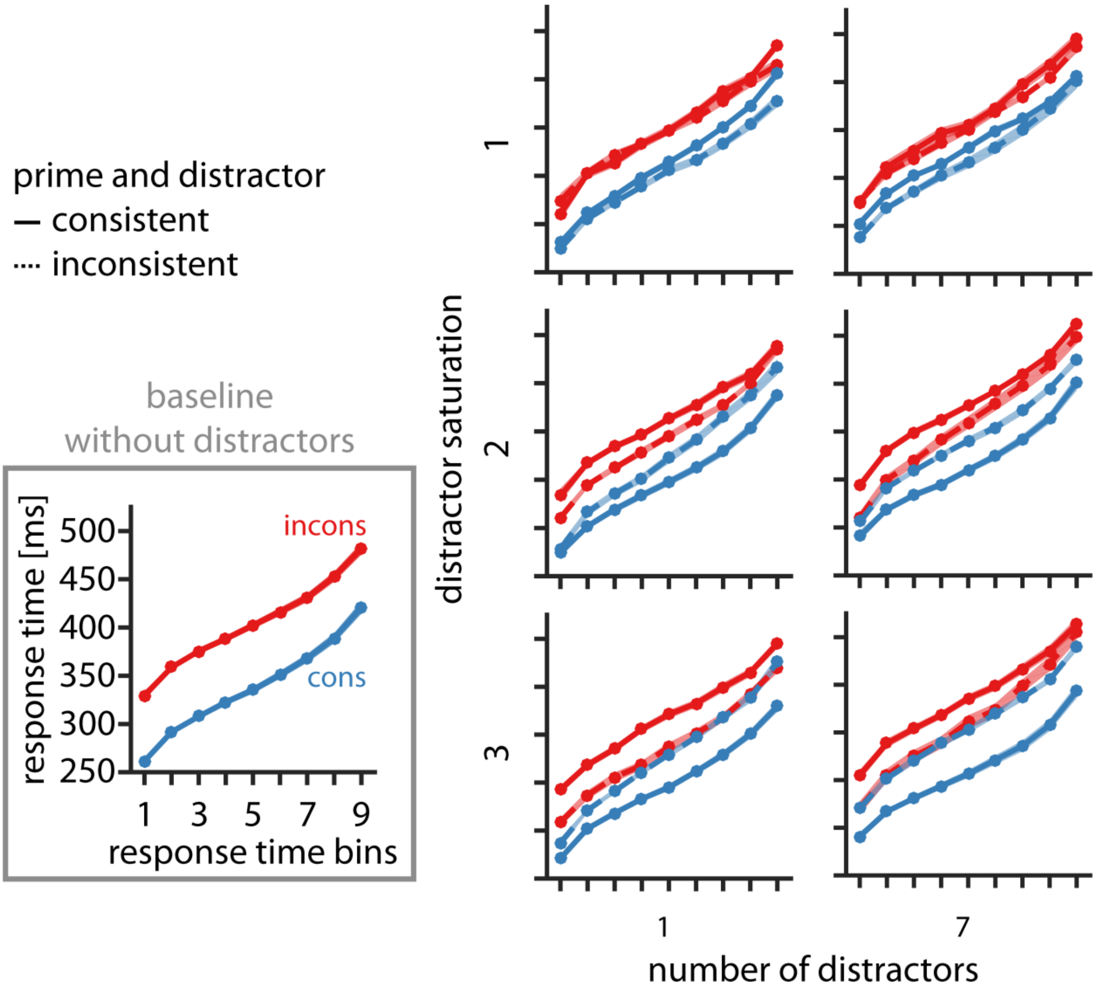

Figure A3. Response times in the prime distractor task in Experiment 1. Response times are plotted as a function of response time bins (from fastest to slowest responses, calculated separately for each participant and condition), line color denotes prime-target consistency (consistent: blue, inconsistent: red), line style denotes prime-distractor consistency (consistent: solid, inconsistent: dashed). The baseline without distractors is shown within the grey frame, the other line graphs show response times as a function of distractor saturation (rows) and number of distractors (columns). Transparent error margins denote standard errors

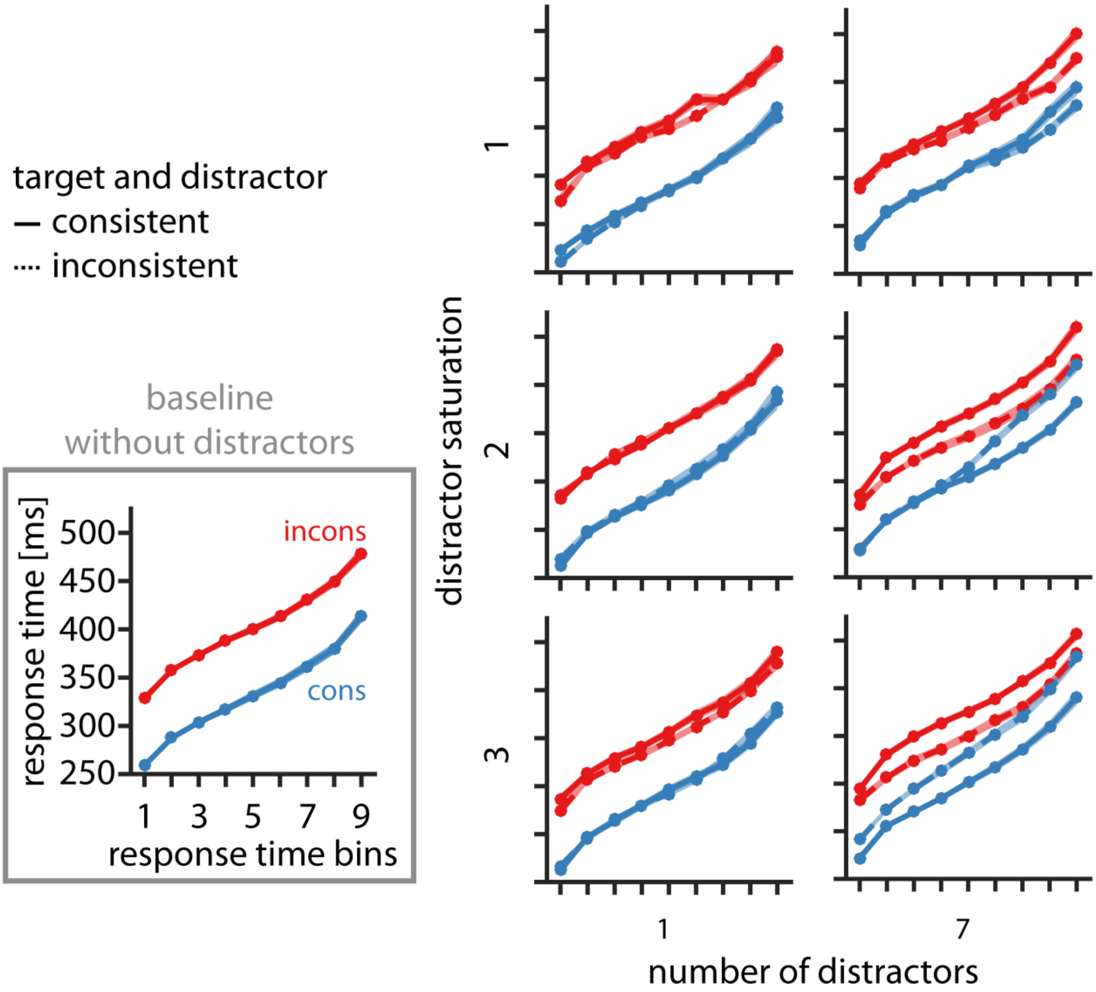

Figure A4. Response times of the target distractor task in Experiment 1. For details see Figure A3.

Table A3. Mean response time (*RT*) and standard deviation (*SD RT*) in Experiment 2.

Affected event	Prime target consistency	Color of distractor	No of distractors	Saturation of distractors	RT [ms]	SD RT [ms]
Prime	cons		0		452	118
		grey	6	1	470	110
		same color	6	2	448	111
				3	437	102
		other color	6	2	488	103
				3	493	110
	incons		0		535	109
		grey	6	1	540	107
		same color	6	2	528	110
				3	530	110
		other color	6	2	545	116
				3	541	117
Target	cons		0		465	120
		grey	6	1	495	117
		same color	6	2	473	121
				3	475	109
		other color	6	2	525	132
				3	531	130
	incons		0		557	126
		grey	6	1	576	134
		same color	6	2	573	120
				3	574	127
		other color	6	2	574	135
				3	571	123

Table A4. Mean error rate (*ER*) in Experiment 2.

Affected event	Prime target consistency	Color of distractor	No of distractors	Saturation of distractors	ER [%]
Prime	cons		0		7.4
		grey	6	1	9.4
		same color	6	2	5.7
				3	5.5
		other color	6	2	9.1
				3	13.1
	incons		0		15.8
		grey	6	1	17.6
		same color	6	2	12.5
				3	16.5
		other color	6	2	18.4
				3	21.5
Target	cons		0		7.4
		grey	6	1	8.2
		same color	6	2	8.2
				3	6.9
		other color	6	2	10.5
				3	13.6
	incons		0		18.9
		grey	6	1	19.0
		same color	6	2	18.2
				3	17.5
		other color	6	2	17.2
				3	18.9