Proactive and reactive stopping when distracted: An attentional account

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Performance in response-inhibition paradigms is typically attributed to inhibitory control. Here we examined the idea that stopping may largely depend on the outcome of a sensory detection process. Subjects performed a speeded go task, but they were instructed to withhold their response when a visual stop signal was presented. The stop signal could occur in the centre of the screen or in the periphery. On half of the trials, perceptual distractors were presented throughout the trial. We found that these perceptual distractors impaired stopping, especially when stop signals could occur in the periphery. Furthermore, the effect of the distractors on going was smallest in the central stop-signal condition, medium in a condition in which no-signals could occur, and largest in the condition in which stop signals could occur in the periphery. The results show that an important component of stopping is finding a balance between ignoring irrelevant information in the environment and monitoring for the occurrence of occasional stop signals. These findings highlight the importance of sensory detection processes when stopping and could shed new light on a range of phenomena and findings in the response-inhibition literature.

Keywords: perceptual distraction, response inhibition, proactive control, response strategies, signal monitoring

Goal-directed behaviour requires an executive control system that allows us to ignore irrelevant information, replace responses, and adjust processing strategies in demanding situations. Here, we investigated how these control functions interact in a stop-signal task, which is a popular tool to examine the behavioural and neural correlates of inhibition in healthy and clinical populations (Verbruggen & Logan, 2008). Researchers typically attribute performance in this task, and in related paradigms, to the effectiveness of a single inhibitory control function. But by referring to a general construct such as inhibition, we cannot adequately explain stop-signal performance. We have recently proposed a theoretical framework which proposes that various forms of action control depend on three basic cognitive processes: signal detection, action selection, and action execution. These processes are modulated via correction- or evaluation mechanisms, preparation, task rules maintained in memory, and learning (Verbruggen, McLaren, Chambers, in press). The aim of this framework is to eliminate the control homunculi from theories of action control.

In the present study, we tested part of this framework by demonstrating that stopping critically depends on signal detection. In a stop-signal task, subjects respond to a go stimulus on no-signal trials. On a random selection of the trials (stop-signal trials), a stop signal is presented after a variable delay (stop-signal delay; SSD), which instructs subjects to withhold their response to the go stimulus. The first index of 'inhibitory' control is the probability of responding on stop-signal trials, p(respond|signal) (Logan & Cowan, 1984). The second index of 'inhibitory' control is an estimate of the covert latency of the stop process, stop-signal reaction time (SSRT). P(respond|signal) and SSRT are both measures of *reactive* control on stop-signal trials. The third index is go reaction time (RT) on no-signal trials. RT is typically longer in blocks in which stop signals can occur than in blocks in which no signals occur. This RT difference has been interpreted as a measure of *proactive* control: people increase response thresholds and generally suppress motor output in situations in which stop signals can occur, compared with situations in which they can always respond (e.g. Cai, Oldenkamp, & Aron, 2011; Jahfari et al., 2012; Verbruggen & Logan, 2009). Thus, there are three

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main dependent variables in a stop-signal task, and most researchers use them to study the inhibition of motor output. However, our theoretical framework states that non-inhibitory processes also play a critical role in stopping responses. The first step in successfully cancelling a response is nearly always detecting the stop signal (e.g. a traffic light turning red or noticing an obstacle on the road). Computational work even suggests that most of SSRT is occupied by afferent or sensory processes (Boucher, Palmeri, Logan, & Schall, 2007; Salinas & Stanford, 2013). Thus, despite the fact that the contribution of non-motor processes is largely neglected in the literature, it appears that stopping on signal trials largely depends on the outcome of sensory processes. Because a failure to detect the signal quickly could have important negative consequences, people may also adjust attentional settings in advance when they expect a stop signal (e.g. preparing oneself to detect the red light or directing spatial attention to the location of possible obstacles). In other words, proactive control may also involve adjusting perceptual processes.

We used a perceptual load manipulation in a stop-signal task to demonstrate that perceptual processes are a key component of both reactive and proactive control in response-inhibition paradigms. Subjects responded to centrally presented words on no-signal trials (Fig1). In some blocks, a stop signal was presented on a random 33% of the trials. There were three types of blocks: *central-signal* blocks, in which a visual stop signal could occur in the centre of the screen, *non-central signal* blocks, in which a visual stop signal could occur in the periphery, and *no-signal* blocks, in which no stop signals could occur. On a random 50% of the no-signal and signal trials, visual distractors were presented. Based on previous work, we assumed that subjects would focus their attention on the centre of the screen (i.e. narrow the 'attentional spotlight') when distractors appeared.

To examine the role of stop-signal detection, we estimated SSRT as a function of distractor presentation and stop-signal type[1]. Narrowing the focus of attention on distractor trials would make detection of stop signals in the periphery harder. Consequently, our attentional account of reactive stopping predicts that the effect of distractors on SSRTs will be larger in non-central signal blocks than in central-signal blocks.

To examine proactive attentional control adjustments, we compared reaction time on no-signal trials in the three signal conditions. Our attentional account predicts that subjects would normally direct their attention to the location of the stop signal. But in non-central-signal blocks, this creates a trade-off between stop-signal detection and interference control: On the one hand, subjects try to widen the attentional focus to detect stop signals in the periphery; on the other hand, they try to narrow their focus to avoid processing of distractors. These opposing demands are expected to result in a larger distractor effect on no-signal performance in non-central signal blocks than in no-signal blocks without the opposing attentional demands. By contrast, the proactive attentional adjustments could result in a smaller distractor effect in central-signal blocks than in no-signal blocks. In the no-signal blocks, a narrow focus of attention is not strictly required, especially because the stimuli of the primary task are presented above and below the centre of the screen. In the central stop-signal blocks, subjects are strongly encouraged by the task demands to focus on the centre of the screen. Consequently, the distractor effect would be smaller in central-signal blocks than in no-signal blocks.

Experiment

Method

Subjects. Twenty-four students from University of Exeter participated for monetary compensation (£6). Two subjects were replaced because the percentage of correct go trials was ≤ 75%. In Supplementary Material, we present the data with these subjects included. The target sample size and exclusion criteria were decided in advance of data collection.

Apparatus and stimuli. The experiment was run on a PC using Psychtoolbox (Brainard, 1997). The stimuli were presented on a 17-in. CRT monitor. The go stimuli were 54 four-letter words (Supplementary Material). For every subject, we created 9 subsets of 6 words (one subset per block)[2]. On each trial, two words were presented in white lowercase font (Courier 16 point; visual angle: 1.5°x0.4°) on a black background (Fig1). One word referred to a natural object, and the other to a man-made object. The words appeared on either side (distance: 0.6°) of a central white line (1.8°), inside a white rectangle (10.5°x10.5°). Half of the subjects responded to the location of the natural object; the other half to the location of the man-made object. They responded by pressing the Up or Down arrow keys of a keyboard using the right index finger. On distractor trials, 20 randomly generated two-letter Uppercase strings (Courier 16; 0.8°x0.5°) were presented at random locations within the square. To avoid overlap between the distractors and words, the centre of the distractors was outside a smaller central region (3.1°x3.1°)[3].

An EyeLink 1000 Desktop Mount camera system (SR Research, Ottawa, Canada), calibrated before each block, tracked the gaze position of the right eye during the whole block.

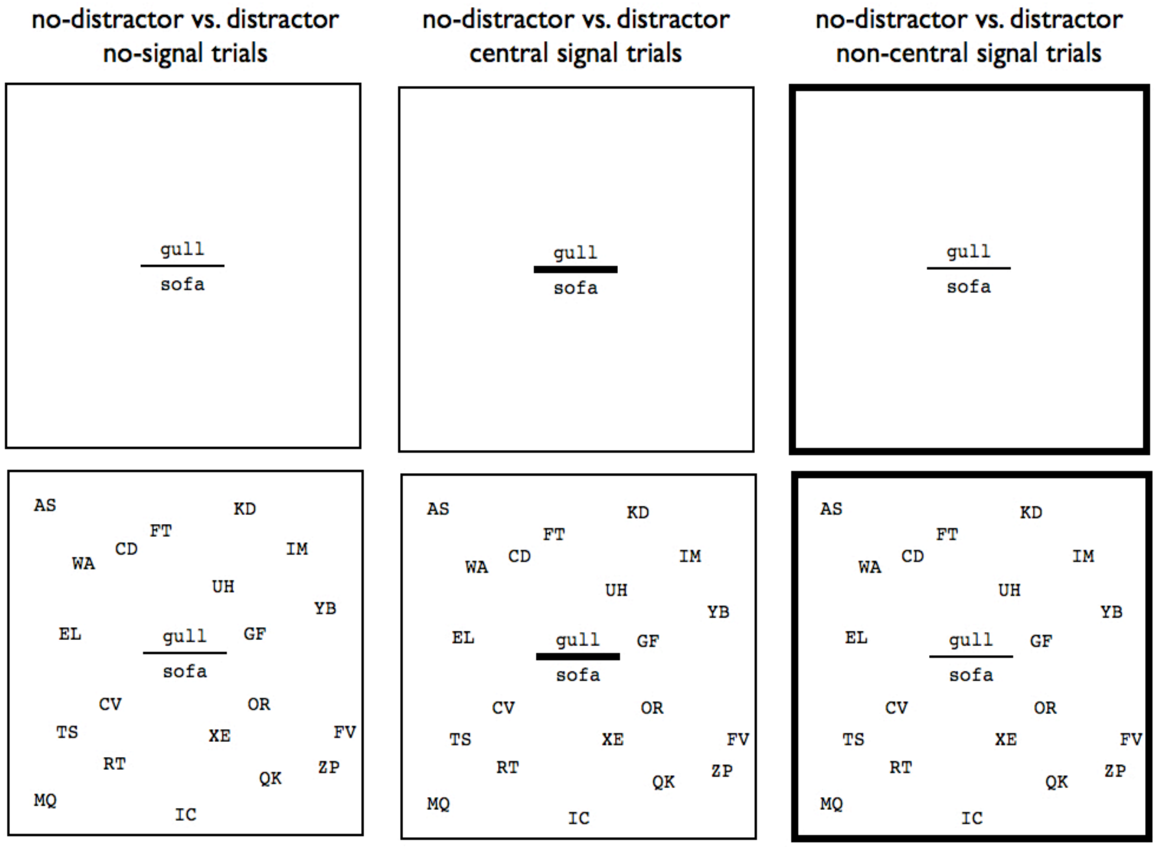

Figure 1: Examples of the six possible trials types (see Methods for further details). On no-signal trials, half of the subjects responded to the location of the natural object; the other half to the location of the man-made object. On distractor trials, random two-letter strings appeared at random locations every 100 ms. On signal trials in the central signal condition, the central line turned bold after a variable delay (SSD); on signal trials in the non-central condition, the large square turned bold after the SSD. On such signal trials, subjects tried to withhold a response. Stop signals always occurred after the presentation of the go stimulus and the distractors. For display purposes, foreground and background colours are switched (i.e. in the experiment, white stimuli appeared against a black background). A short Quicktime movie with an example of a trial sequence is deposited on the Open Research Exeter data repository (http://hdl.handle.net/10871/13401). Please note that this is an example of a trial in the pilot study; consequently, there are only 15 distractors).

Procedure. All trials started with the presentation of the square and the central horizontal line. After 250 ms, the two words appeared. On half of the trials in each block (distractor trials), 20 distractors also appeared. Every 100 ms, 20 new distractors appeared at new random locations to ensure a perceptual load during the whole trial; this was required because the delay between the go stimulus and the stop signal varied (see below). After 1,500 ms, the words and distractors were replaced by a feedback message (on no-signal trials: 'correct', 'incorrect', or 'not quick enough' in case they did not respond before the end of the trial; on signal trials: 'correct stop' or 'failed stop'), which remained on the screen for 500 ms. The feedback was presented to encourage fast and accurate responding. The next trial started immediately after the feedback.

In the central- and non-central signal blocks, a stop signal was presented on 33% of the trials (stop-signal trials). In the central-signal blocks, the central line turned bold (1 to 3 pixels) on signal trials; in the non-central signal blocks, the outline of the surrounding square turned bold (1 to 3 pixels). The line(s) turned bold after a variable stop-signal delay (SSD). SSD was initially set at 500 ms, and continuously adjusted according to a tracking procedure to obtain a probability of stopping of .50: SSD decreased by 50 ms when a subject responded on a stop-signal trial, but increased by 50 ms when they successfully stopped. We used separate tracking procedures for central- and non-central signal blocks and for trials with and without distractors.

Each condition consisted of 3 blocks of 108 trials (total number of trials per condition: 324), resulting in 9 blocks overall. Order of the blocks (no-signal, central-signal, non-central-signal) was counterbalanced across subjects (e.g. NS-CS-NCS-NS-CS-NCS-NS-CS-NCS). At the beginning of each block, a message on the screen informed subjects whether central or non-central stop signals could occur. At the end of each block, we presented as feedback to the subject their mean RT on no-signal trials, number of no-signal errors and missed no-signal responses, and percentage of failed stops.

Analyses. All data processing and analyses were completed using R (R Development Core Team, 2008). Proactive response-strategy adjustments could result in a higher percentage of omitted responses as well as higher accuracy (Verbruggen & Logan, 2009), so we distinguished between the proportion of correct no-signal trials and the proportion of missed no-signal trials. SSRTs were estimated using the session-wide integration method (Verbruggen et al., 2013). The distractor effect refers to performance on distractor trials minus performance on no-distractor trials. See Supplementary Material for exploratory analyses of the eye data.

All data files and R scripts used for the analyses of the pilot study and the experiment reported here are deposited on the Open Research Exeter data repository (http://hdl.handle.net/10871/13401).

Results And Discussion

An overview of the data and analyses appears in Tables 1-2. The stopping latencies support the 'attentional' account of reactive control: SSRTs were longer on distractor trials (493 ms) than on no-distractor trials (348 ms), $p < .001$. Importantly, the distractor effect on SSRTs was much larger in non-central signal blocks (253 ms) than in central-signal blocks (37 ms). This interaction was reliable ($p < .001$; Table 2). The attentional account is further supported by the exploratory analyses of the eye data: the frequency of eye movements increased in the non-central-signal condition (Supplementary Material). Compared with previous stop-signal studies, SSRTs were much longer on distractor trials in the non-central signal condition. It is possible that on a proportion of the stop-signal trials with distractors, subjects responded because they did not detect the stop signal in time. This could have inflated SSRT estimates (Band, van der Molen, & Logan, 2003). Thus, the absolute value of SSRTs should be interpreted with caution. But even if SSRT is inflated, the difference between conditions still points to a stopping deficit caused by perceptual factors because responding on a stop-signal trial is generally considered as one of the main indices of control (Logan & Cowan, 1984).

Next, we analysed no-signal RTs. On average, distractors slowed responding on no-signal trials by 70 ms, and RTs were longer in central (975 ms) and non-central signal blocks (987 ms) than in no-signal blocks (754 ms). These main effects were statistically significant (Table 2). Two-tailed t-tests revealed that the difference between the no-signal blocks and the central and non-central signal blocks were significant, $t(23) = 6.87$, $p < .001$, Cohen's d = 1.4, and $t(23) = 7.58$, $p < .001$, Cohen's d = 1.5, respectively. The difference between the two signal conditions was not significant, $t(23) = 1.16$, $p = .26$, Cohen's = 0.2. Consistent with our attentional account, the distractor effect on no-signal trials (i.e. RT distractor minus RT no-distractor) was influenced by the occasional presentation of stop signals in the block: it was smaller in central-signal blocks (58 ms) than in no-signal blocks (70 ms); and was, in turn, smaller in no-signal blocks than in non-central-signal blocks (83 ms). This interaction between block type and distractor was significant ($p < .01$). Follow-up tests showed that the difference between central and non-central blocks was significant, $t(23) = 2.73$, $p = .01$ (one-

Table 1: Probability of an accurate go response [p(correct)], probability of a missed go response [p(miss)], average reaction time (RT) for correct go responses, probability of responding on a signal trial [p(respond)], average stop-signal delay (SSD), stop-signal reaction time (SSRT), and signal-respond reaction time (s-r RT; the latency of incorrectly executed responses) as a function of Stop-signal condition, and Distractor condition. P(correct) is the ratio of the number of correct responses to the number of correct and incorrect responses: p(correct) = correct/(correct + incorrect). P(miss) is the ratio of the number of omitted responses to the total number of no-stop-signal trials: p(miss) = missed/(correct + incorrect + missed). M = mean; sd = standard deviation.

	central signal				no signal				non-central signal			
	no distractor		distractor		no distractor		distractor		no distractor		distractor	
	M	*sd*	*M*	*sd*	*M*	*sd*	*M*	*sd*	*M*	*sd*	*M*	*sd*
p(correct)	0.95	0.05	0.95	0.05	0.96	0.03	0.96	0.02	0.95	0.05	0.96	0.04
p(miss)	0.06	0.05	0.07	0.08	0.02	0.02	0.02	0.03	0.07	0.06	0.08	0.06
RT	946	170	1004	171	719	97	789	97	945	161	1028	156
p(respond)	0.47	0.05	0.46	0.05					0.48	0.06	0.56	0.15
SSD	584	204	590	193					555	229	441	280
SSRT	333	92	370	82					363	130	616	260
s-r RT	844	180	902	163					867	151	965	161

Table 2: Overview of repeated measures analyses of variance performed to compare no-signal and signal performance. Stop-signal condition (central-signal, non-central signal, or no-signal blocks) and distractor (no distractor vs. distractor) are the within-subjects factors. We did not analyse p(miss) because values were low. Note that the main effect of condition for p(correct) was significant when the two outliers were included (*p* = .04). This analysis is presented in the Supplementary Material.

	df 1	*df2*	*SS1*	*SS2*	*F*	*p*	*partial η²*	*generalised η²*
Go accuracy								
signal	2	46	0.004	0.042	1.980	0.150	0.087	0.015
distract	1	23	0.000	0.010	0.070	0.793	0.000	0.000
signal:distract	2	46	0.001	0.020	0.957	0.392	0.048	0.004
Go Reaction Time								
signal	2	46	1,652,647	763,327	49.796	< 0.001	0.684	0.361
distract	1	23	180,077	9,182	451.053	< 0.001	0.951	0.058
signal:distract	2	46	3,969	16,993	5.372	0.008	0.189	0.001
SSRT								
signal	1	23	457826	416327	25.293	< 0.001	0.524	0.167
distract	1	23	502189	200622	57.573	< 0.001	0.715	0.180
signal:distract	1	23	280899	253746	25.461	< 0.001	0.525	0.109

tailed directional t-test: *p* = .006)[4], Cohen's d = .55; the differences between central-signal and no-signal blocks, and between no-signal and non-central blocks were marginally significant; *t*(23) = 1.91, *p* = .07 (one-tailed directional t-test: *p* = .035), Cohen's d = .39, and *t*(23) = 1.81, *p* = .08 (one-tailed directional t-test: *p* = .041), Cohen's d = .37, respectively. Collectively, these RT findings support the 'attentional' account of proactive stopping, which proposes that ignoring distractors and proactive adjustments in stop-signal tasks both involve (re)focusing visual attention.

Conclusions

The present study focused on how perception and executive control interact in a stop-signal task. We can draw two main conclusions. First, our results demonstrate that perceptual distractors cause large stopping deficits. This sheds a new light on a range of phenomena and findings in the response-inhibition literature. For example, stopping is impaired when incongruent distractors are presented (Chambers et al., 2007; Ridderinkhof, Band, & Logan, 1999; Verbruggen, Liefooghe, & Vandierendonck, 2004). This has been attributed to an interaction between inhibitory processes, but our current results suggest that it could have been caused by adjustments of the attentional focus on distractor trials. Similarly, stopping deficits in certain clinical populations could be due to impairments in selective attention, rather than in inhibition (Bekker et al., 2005). More generally, in everyday life stop signals often occur in noisy environments, so the ability to quickly detect a signal amongst perceptual distractors may be key to successful stopping. Although some studies have already focused on stop-signal detection, the role of attention and perception has been largely neglected in the response-inhibition domain. The dominant view is still to attribute differences in stopping latencies to differences in the effectiveness of a single inhibitory control process (Verbruggen et al., in press). The present study provides clear behavioural support for the idea that perceptual processes play an important role in reactive stopping. We strongly urge researchers to consider the possibility that intra- or inter-individual differences in stopping performance could be caused by differences in stop-signal detection rather than inhibition of motor output when they interpret their findings. Other stop-signal studies have used visual go stimuli and auditory stop signals. This requires divided attention, but we see no reason why stimulus detection would be less important in these situations than in situations in which both signals are presented in the same modality.

Second, the results demonstrate that monitoring for signals is an important aspect of proactive control in the stop-signal task. The relative contribution of various control adjustments, such as signal monitoring, increasing thresholds, or suppressing motor output, may depend on task context. This could explain apparent discrepancies between studies. For example, in Verbruggen and Logan (2009), stop signals were loud auditory signals. We found that both RTs and accuracy on no-signal trials increased in signal blocks, which suggests an increase in response threshold. This idea was supported by diffusion-model fits (Logan, Van Zandt, Verbruggen, & Wagenmakers, 2014; Verbruggen & Logan, 2009). In the present study, we found an increase in RT but a small decrease in accuracy (Tables 1-2). This pattern is inconsistent with a response-threshold account. Instead, we propose that the slowing here was mainly caused by monitoring for stop signals. Thus, proactive control in the stop-signal task could be implemented differently, depending on the task context.

The results are consistent with our recently proposed theoretical framework of action control (Verbruggen et al., in press). We have argued that basic cognitive processes, such as stimulus detection and action selection, underlie most forms of action control, including outright stopping. These processes are, in turn, modulated by processes that operate over a slower time scale, including proactive or preparatory control. The present study highlights the importance of focusing on the underlying processes, such as stimulus detection, rather than general functions, such as response inhibition, as it provides a more precise account of performance.

Footnotes

1. To obtain reliable SSRT estimates with a relatively low number of signal trials, we used a staircase tracking procedure (see the method section). SSD is continuously adjusted to obtain a probability of stopping of .50. Consequently, we could not use average p(respond|signal) as an index of inhibitory control in this study.
2. This study is part of a larger project that focuses on how stopping and both general- and item-specific learning influence decision-making in various domains (see e.g. Verbruggen, Adams, Chambers, 2012). To allow comparisons with our other studies, we used a decision-making task in which subjects had to select one of two words that could appear above or below the fixation line.
3. The size of the stimuli and the number of distractors were determined after a pilot study. In this pilot study, we found a small numerical interaction between proactive and reactive stopping and distractor interference, but which failed to reach statistical significance (see Supplementary Material). Therefore, in the experiment reported here we sought to increase the effect size by (a) increasing the size of the outer square, and consequently, the distance between the centre of the screen and the non-central stop signal; (b) increasing the number of distractors; and (c) reducing the width of the stop signals. If perceptual processing is a critical component of reactive and proactive inhibitory control, then increasing the perceptual demands should influence both.
4. The attentional account makes strong predictions about the direction of the distractor effect. No differences in distractor effects or differences in the opposite direction (i.e. the smallest distractor effect in the non-central condition) would argue against the attentional account of proactive control. Therefore, we report both the two-tailed p-values and the p-values of planned one-directional t-tests.

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Supplementary Material

Pilot study

Twenty-four students from the University of Exeter participated for monetary compensation (£6). One subject was replaced because their SSRT was 6 standard deviations above the average in the non-central distractor condition. Inclusion of this subject did not alter the results in a meaningful way. The procedure was similar to the one used in the main experiment reported in the manuscript, except for a few differences: the size of the outer square was smaller (7.5°x7.5°), the stop signals were wider (5 pixels), the number of distractors was lower (15), and the centre of the distractors was outside a smaller central region (2.1°x2.1°).

Relevant no-signal and signal data appear in Tables S1-2, and Table S3 provides an overview of the repeated Analyses of Variance performed to compare no-signal and signal performance.

Subjects required more time to stop their response on distractor trials (371 ms) than on no-distractor trials (272 ms), $p < .05$ (Table S3). This distractor effect was numerically larger in the non-central signal condition (113 ms) than in the central signal condition (85 ms), but this difference was not significant ($p = .18$; Table S3). The main effect of signal was also not significant.

Average RT of correct no-signal trials was longer in the central (921 ms) and non-central (906 ms) signal blocks than in no-signal blocks (768 ms). The presentation of distractors slowed responses (no-distractor trials: 836 ms; distractor trials: 893 ms). Both main effects were significant ($p < .001$; Table S3). Distractors had a numerically larger effect in non-central signal blocks (64 ms) than in no-signal (55 ms) blocks, but the distractor effect was similar in no-signal and central-signal blocks (52 ms), and the overall interaction between distractor and block type was not significant ($p = .23$).

In summary, we found some differences between signal conditions but the crucial interactions between block type and distractor presentation did not reach significance. Therefore, in the experiment reported in the main manuscript we (a) increased the size of the outer square, and consequently, the distance between the centre of the screen and the non-central stop signal; (b) increased the number of distractors; and (c) reduced the width of the stop signals. By increasing the perceptual demands, we expected more pronounced interactions between perceptual-interference control and reactive and proactive control.

Additional behavioural analyses

In the experiment reported in the manuscript, 2 subjects were replaced because the percentage of correct go trials was ≤ 75%. In Tables S1 and S2, we show the group averages for all conditions when these subjects were included in the analyses. We also reran all analyses (Table S3). Exclusion of these subjects did not alter the results substantially. All main effects and interactions were significant for no-signal RT and SSRT. This is consistent with the results reported in the main text. The Go Accuracy analyses now revealed a significant main effect of signal block, which suggests that accuracy was lower in the signal blocks than in the no-signal blocks (see also Table S1).

Go stimuli

We used the 54 words in this study.
Natural: gull, pear, wasp, moth, calf, plum, crow, slug, leaf, dove, toad, swan, crab, pony, deer, worm, lamb, goat, frog, hawk, rice, lion, wolf, duck, bull, bear, tree
Man-made: tuba, tram, coil, mast, tile, gong, harp, wand, vase, raft, sofa, drum, fork, sock, coin, jeep, shed, pill, barn, sink, flag, pipe, bowl, belt, shoe, desk, book

Analyses of the eye data

An EyeLink 1000 Desktop Mount camera system (SR Research, Ottawa, Canada), calibrated before each block, tracked the gaze position of the right eye during the whole block (sampling rate: 500 Hz). The EyeLink was calibrated and controlled via Psychtoolbox (Cornelissen, Peters, & Palmer, 2002). Eye data were subsequently exported using the Eyelink Data Viewer (SR Research, Ottawa, Canada): for each subject, we generated a file with information about all fixations and a file with trial information and the sequence of events. We integrated these files using R, and created a large data file for further analyses.

In the analyses of the eye data, we excluded subjects when no fixation was registered at the beginning of an event (e.g. presentation of the go stimulus) on more than 15% of the trials, as this could indicate that eye-movement registration was suboptimal. Based on this criterion, we excluded 5 subjects in the pilot and 6 subjects in the main experiment. Note that inclusion of those subjects did not alter the results much (not shown). We also excluded all fixations that were supposedly off screen (0.2% in the pilot and 0.5% in the main experiment).

In the analyses, we focused on the number of the fixations and the fixation location for three intervals: (1) the fixation interval, (2) the interval between the presentation of the go stimulus and the response on no-signal trials, and (3) after the stop signal. In the pilot, eye movements made 400 ms after the presentation of the stop signal

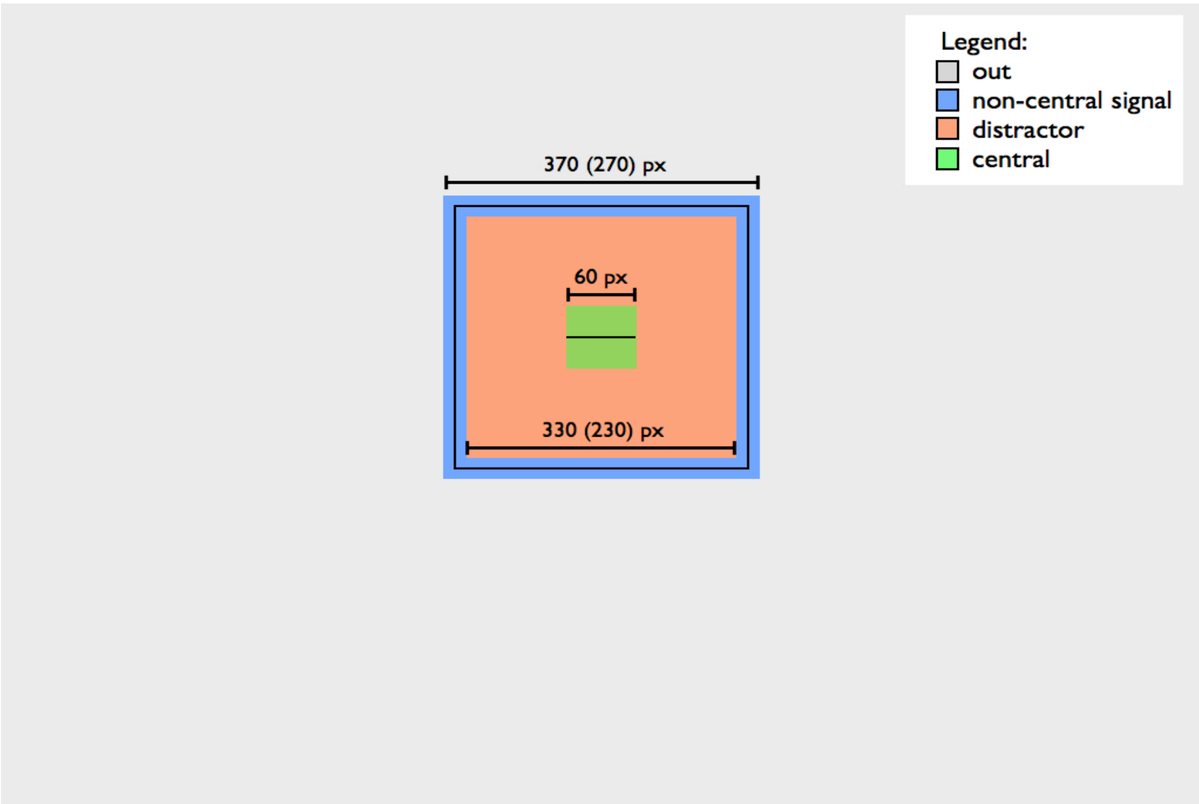

Figure S1: To analyse fixation location, we predefined 4 regions (squares): a central region around the central stop signal and the two words, a region with the distractors, a region around the non-central stop-signal, and an outside region. Size of each square is in pixels because pixel coordinates were used for registration of fixation location (values pilot between brackets). See main text for visual angles. Screen size: 1024 x 768 pixels.

were excluded; in the main experiment, we used 700 ms as a cut-off. These values were based on the largest average SSRT value (in both the pilot study and the main experiment, this was SSRT in the non-central distractor condition).

The number of fixations and fixation location for each trial type (distractor vs. no-distractor) and block type (central-signal, non-central signal, and no-signal) could provide further information on how subjects controlled perceptual interference and monitored for the occurrence of occasional stop signals. For example, people may narrow attention to reduce distractor processing; potentially, this could also reduce the number of fixations towards distractors. Similarly, monitoring for central stop signals could lead to more fixations on central locations in central-signal blocks than in no-signal blocks. By contrast, detecting non-central stop signals requires a wider attentional focus; and this could result in more fixations towards the non-central square in non-central signal blocks than in the two other block types.

The descriptive statistics are in Tables S4 (pilot) and S6 (main experiment); the inferential statistics are in Tables S5 (pilot) and S7 (main experiment). If the number of fixations for a particular interval = 1, then the subject did not move their eyes during the whole interval (i.e. the eyes remained fixated on the region that was fixated before the interval had started). Fixation location can be analysed in different ways. Here we calculated the average distance between the fixated location and the centre of the screen [distance = sqrt(x-coordinate^2 + y-coordinate^2)]. In Tables S4 and S6, we also show the proportion of the fixations that fell within 4 pre-defined regions: a region in the centre of the screen (around the stop-signal and the two words), a region in which the distractors occurred, a region around the non-central stop-signal, and an outside region; these regions with their coordinates are depicted in Figure S1.

As can be seen in the tables, subjects did not make many eye movements during the intervals of interest, and they fixated on the centre of the screen most of the time. In the pilot study, the numerical differences between signal and distractor conditions were very small. All p values $\geq .05$, except for the effect of signal type on the number of fixations on signal trials: subjects tended to make more eye movements in non-central signal trials than in central-signal trials, $p = .015$.

In the main experiment, the differences between signal conditions were slightly larger (Table S6). The average distance between fixated location and the central location was larger in non-central blocks than in central-signal and no-signal blocks; they also made more eye movements in the non-central blocks (see highlighted cells in Table S6). These differences were reliable (p's < .03; Table S7). This is consistent with the idea that subjects widened attention in the non-central signal condition. On stop-signal trials, subjects also made more eye movements towards the outer square in non-central signal blocks than in central-signal blocks (Tables S6-7; p's < .04). In other words, when stop signals in the periphery were harder to detect, subjects were more likely to move their eyes to the location of the stop signal. Despite differences being small, the results of the main experiment are largely consistent with the 'attentional' account.

Reference:

Cornelissen, F. W., Peters, E. M., & Palmer, J. (2002). The eyelink toolbox: Eye tracking with MATLAB and the psychophysics toolbox. Behaviour Research Methods, 34, 613-7

Table S1: Probability of an accurate go response [p(correct)], probability of a missed go response [p(miss)], and average reaction time for correct go responses, as a function of Experiment, Stop-signal condition, and Distractor condition. In the main experiment, all subjects (including outliers) were included. P(correct) is the ratio of the number of correct responses to the number of correct and incorrect responses: p(correct) = correct/(correct + incorrect). P(miss) is the ratio of the number of omitted responses to the total number of no-stop-signal trials: p(miss) = missed/(correct + incorrect + missed). M = mean; sd = standard deviation; N = total number of subjects.

	p(correct)		*p(miss)*		*reaction time*	
	M	*sd*	*M*	*sd*	*M*	*sd*
Pilot study						
central signal						
no distractor	0.96	0.03	0.04	0.04	894	168
distractor	0.96	0.04	0.05	0.04	947	164
non-central signal						
no distractor	0.96	0.04	0.04	0.03	874	149
distractor	0.96	0.04	0.04	0.03	938	145
no signal						
no distractor	0.95	0.04	0.02	0.02	740	75
distractor	0.96	0.03	0.02	0.03	795	80
Main experiment (N = 26)						
central signal						
no distractor	0.946	0.05	0.07	0.06	955	173
distractor	0.943	0.05	0.08	0.08	1014	172
non-central signal						
no distractor	0.942	0.05	0.08	0.07	956	161
distractor	0.949	0.04	0.10	0.09	1039	159
no signal						
no distractor	0.962	0.03	0.03	0.03	730	101
distractor	0.958	0.03	0.03	0.03	803	105

Table S2: Probability of responding on a signal trial [p(respond)], average stop-signal delay (SSD), stop-signal reaction time (SSRT), and signal-respond reaction time (i.e. latency of incorrectly executed responses) as a function of Experiment, Stop-signal condition, and Distractor condition. In the main experiment, all subjects (including outliers) were included. M = mean; sd = standard deviation; N = number of subjects.

	p(respond)		*SSD*		*SSRT*		*signal-respond RT*	
	M	*sd*	*M*	*sd*	*M*	*sd*	*M*	*sd*
Pilot study								
central signal								
no distractor	0.48	0.05	591	185	273	58	778	155
distractor	0.48	0.05	560	163	358	65	829	140
non-central signal								
no distractor	0.47	0.05	571	185	270	79	757	140
distractor	0.48	0.06	529	189	383	81	829	124
Main experiment (N = 26)								
central signal								
no distractor	0.47	0.05	588	202	337	89	853	178
distractor	0.46	0.05	596	195	376	83	916	170
non-central signal								
no distractor	0.48	0.06	588	202	337	89	876	152
distractor	0.55	0.14	596	195	376	83	978	164

Table S3: Overview of repeated measures analyses of variance performed to compare no-signal and signal performance in the pilot study and the main experiment when all subjects were included. Stop-signal condition (central-signal, non-central signal, or no-signal blocks) and distractor (no distractor vs. distractor) are the within-subjects factors. We did not analyse p(miss) because values were low. *gen.* η^2 = generalised eta squared.

	df 1	*df2*	*SS1*	*SS2*	*F*	*p*	*partial* η^2	*gen.* η^2
Pilot study								
Go accuracy								
signal	2	46	0.001	0.017	0.729	0.488	0.056	0.003
distract	1	23	0.000	0.010	0.726	0.403	0.000	0.002
signal:distract	2	46	0.001	0.013	2.046	0.141	0.071	0.006
Go Reaction Time								
signal	2	46	683878	410529	38.314	0.000	0.625	0.212
distract	1	23	116204	14700	181.812	0.000	0.888	0.044
signal:distract	2	46	894	13705	1.500	0.234	0.061	0.000
SSRT								
signal	1	23	2884	86336	0.768	0.390	0.032	0.006
distract	1	23	235859	43490	124.735	0.000	0.844	0.334
signal:distract	1	23	4330	53409	1.865	0.185	0.075	0.009
Main experiment (N = 26)								
Go accuracy								
signal	2	50	0.007	0.054	3.438	0.040	0.115	0.025
distract	1	25	0.000	0.012	0.003	0.954	0.000	0.000
signal:distract	2	50	0.001	0.024	1.010	0.372	0.040	0.003
Go Reaction Time								
signal	2	50	1758393	791673	55.528	0.000	0.690	0.348
distract	1	25	199240	9451	527.021	0.000	0.955	0.057
signal:distract	2	50	3917	19970	4.903	0.011	0.164	0.001
SSRT								
signal	1	25	481344	421757	28.530	0.000	0.929	0.172
distract	1	25	555130	202043	68.690	0.000	0.533	0.193
signal:distract	1	25	299714	254294	29.470	0.000	0.733	0.115

Table S4: An overview of the number of fixations, average distance between fixation location and centre of the screen (in pixels), and the proportion of the fixations that fell within our 4 pre-defined regions, per event (fixation interval, go stimulus-response interval on no-signal trials, and after the presentation of the stop signal) and for each signal and distractor condition in the pilot study. NCS = non-central stop-signal region; M = mean; sd = standard deviation.

	Number of Fixations		Distance		Probability central region		Probability distractor region		Probability NCS region		Probability outside region	
	M	*sd*	*M*	*sd*	*M*	*sd*	*M*	*sd*	*M*	*sd*	*M*	*sd*
Fixation interval												
Central	1.09	0.06	31.13	9.33	0.73	0.20	0.27	0.20	0.00	0.00	0.00	0.00
Non-central	1.09	0.06	31.60	11.21	0.71	0.22	0.28	0.22	0.00	0.00	0.01	0.01
No-signal	1.08	0.07	34.75	12.61	0.67	0.26	0.32	0.26	0.00	0.01	0.01	0.01
Go stimulus												
Central, no distractor	1.57	0.30	31.33	9.98	0.71	0.20	0.29	0.20	0.00	0.00	0.00	0.00
Central,distractor	1.54	0.23	30.29	9.47	0.73	0.19	0.27	0.19	0.00	0.00	0.00	0.00
Non-central, no distractor	1.63	0.32	31.33	10.87	0.70	0.23	0.30	0.23	0.00	0.00	0.00	0.01
Non-central,distractor	1.62	0.28	31.31	10.60	0.71	0.21	0.29	0.21	0.00	0.00	0.00	0.01
No-signal, no distractor	1.55	0.21	35.08	13.17	0.65	0.25	0.34	0.25	0.00	0.00	0.01	0.01
No-signal,distractor	1.54	0.20	34.47	12.61	0.67	0.25	0.32	0.25	0.00	0.00	0.00	0.01
Stop signal												
Central, no distractor	1.18	0.09	30.74	10.05	0.72	0.21	0.27	0.21	0.00	0.00	0.00	0.01
Central,distractor	1.17	0.08	29.59	8.92	0.75	0.19	0.25	0.19	0.00	0.00	0.00	0.00
Non-central, no distractor	1.23	0.10	30.86	10.34	0.71	0.22	0.29	0.22	0.00	0.00	0.00	0.00
Non-central,distractor	1.21	0.13	30.45	9.31	0.72	0.21	0.28	0.21	0.00	0.00	0.00	0.01

Table S5: Overview of Analyses of Variance performed to compare number of fixations and average distance in the pilot study.

	df 1	*df2*	*SS1*	*SS2*	*F*	*p*	*partial η²*	*gen. η²*
Fixation interval								
Number of fixations								
signal	2	36	0.003	0.025	1.833	0.175	0.107	0.012
Distance								
signal condition	2	36	146.549	1255.236	2.102	0.137	0.105	0.021
Go stimuli								
Number of fixations								
signal	2	36	0.124	0.683	3.257	0.050	0.154	0.016
distract	1	18	0.009	0.216	0.787	0.387	0.040	0.001
signal:distract	2	36	0.002	0.132	0.234	0.793	0.015	0.000
Distance								
signal condition	2	36	352.717	2175.221	2.919	0.067	0.140	0.025
distract	1	18	8.848	44.397	3.587	0.074	0.166	0.001
signal:distract	2	36	5.040	60.837	1.491	0.239	0.077	0.000
Stop signal								
Number of fixations								
signal	1	18	0.036	0.090	7.272	0.015	0.286	0.046
distract	1	18	0.004	0.047	1.438	0.246	0.078	0.005
signal:distract	1	18	0.000	0.059	0.013	0.909	0.000	0.000
Distance								
signal	1	18	4.552	698.701	0.117	0.736	0.006	0.001
distract	1	18	11.629	60.573	3.456	0.079	0.161	0.002
signal:distract	1	18	2.639	83.037	0.572	0.459	0.031	0.000

Table S6: An overview of the number of fixations, average distance between fixation location and centre of the screen (in pixels), and the proportion of the fixations that fell within our 4 predefined regions, per event (fixation interval, go stimulus-response interval on no-signal trials, and after the presentation of the stop signal) and for each signal and distractor condition in the main experiment. NCS = non-central stop-signal region; M = mean; sd = standard deviation. Contrasts discussed in text are in bold.

	Number of Fixations		Distance		Probability central region		Probability distractor region		Probability NCS region		Probability outside region	
	M	*sd*	*M*	*sd*	*M*	*sd*	*M*	*sd*	*M*	*sd*	*M*	*sd*
Fixation interval												
Central	1.13	0.10	36.03	11.49	0.67	0.23	0.31	0.23	0.00	0.01	0.01	0.01
Non-central	1.18	0.14	35.99	10.79	0.68	0.20	0.31	0.19	0.00	0.00	0.01	0.01
No-signal	1.08	0.06	37.22	15.93	0.66	0.28	0.33	0.28	0.00	0.00	0.01	0.02
Go stimulus												
Central, no distractor	**1.40**	0.32	**38.84**	16.94	0.66	0.24	0.32	0.23	0.00	0.01	0.02	0.04
Central,distractor	**1.39**	0.34	**36.95**	15.96	0.68	0.23	0.30	0.22	0.00	0.01	0.02	0.04
Non-central, no distractor	**1.80**	0.62	**50.03**	26.07	0.61	0.23	0.34	0.20	0.02	0.03	0.02	0.05
Non-central,distractor	**1.75**	0.60	**51.59**	30.28	0.61	0.25	0.33	0.21	0.02	0.03	0.03	0.07
No-signal, no distractor	**1.42**	0.22	**37.58**	15.57	0.64	0.27	0.35	0.27	0.00	0.00	0.01	0.02
No-signal,distractor	**1.40**	0.26	**37.44**	15.61	0.65	0.26	0.34	0.26	0.00	0.00	0.01	0.02
Stop signal												
Central, no distractor	**1.27**	0.15	**37.77**	12.82	0.65	0.24	0.34	0.24	0.01	0.02	0.01	0.03
Central,distractor	**1.24**	0.18	**34.91**	12.19	0.68	0.24	0.31	0.24	0.00	0.01	0.01	0.03
Non-central, no distractor	**1.45**	0.32	**51.88**	35.78	0.61	0.26	0.33	0.21	0.03	0.05	0.03	0.09
Non-central,distractor	**1.41**	0.30	**54.37**	35.74	0.60	0.26	0.33	0.23	0.03	0.04	0.04	0.10

Table S7: Overview of Analyses of Variance performed to compare number of fixations and average distance in the main experiment. Contrasts discussed in text are in bold.

	df 1	*df2*	*SS1*	*SS2*	*F*	*p*	*partial η²*	*gen. η²*
Fixation interval								
Number of fixations								
signal condition	2	36	0.090	0.139	11.649	0.000	0.393	0.127
Distance								
signal condition	2	36	18.644	1423.725	0.236	0.791	0.013	0.002
Go stimuli								
Number of fixations								
signal	**2**	**36**	**3.478**	**7.434**	**8.421**	**0.001**	**0.319**	**0.153**
distract	1	18	0.023	0.232	1.809	0.195	0.090	0.001
signal:distract	2	36	0.008	0.223	0.671	0.517	0.035	0.000
Distance								
signal	**2**	**36**	**4358.285**	**19593.499**	**4.004**	**0.027**	**0.182**	**0.084**
distract	1	18	0.735	233.029	0.057	0.814	0.003	0.000
signal:distract	2	36	56.643	469.107	2.173	0.128	0.108	0.001
Stop signal								
Number of fixations								
signal	**1**	**18**	**0.607**	**0.828**	**13.202**	**0.002**	**0.423**	**0.119**
distract	1	18	0.020	0.144	2.447	0.135	0.122	0.004
signal:distract	1	18	0.000	0.064	0.052	0.822	0.000	0.000
Distance								
signal	**1**	**18**	**5353.255**	**19502.093**	**4.941**	**0.039**	**0.215**	**0.094**
distract	1	18	0.670	216.162	0.056	0.816	0.003	0.000
signal:distract	1	18	136.062	485.052	5.049	0.037	0.219	0.003