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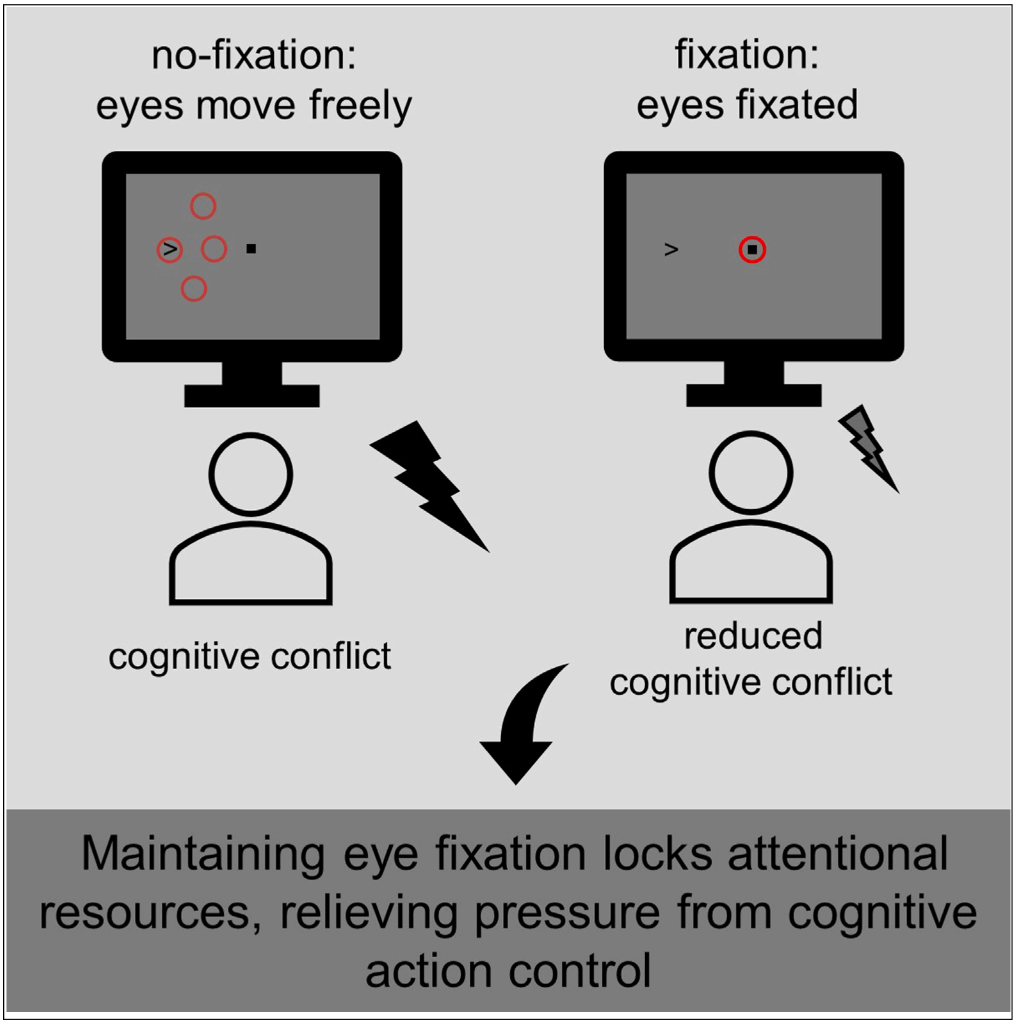
Maintaining eye fixation relieves pressure of cognitive action control



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Highlights

- Cognitive control allows to act based on intention rather than stimulus information
- Maintaining the eyes fixated supports the resolution of spatial cognitive conflicts
- Fixating the eyes seems to lock attentional resources contributing to the conflict
- This facilitates goal-directed action by relieving pressure from cognitive control

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Maintaining eye fixation relieves pressure of cognitive action control

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SUMMARY

Cognitive control enables humans to behave guided by their current goals and intentions. Cognitive control in one task generally suffers when humans try to engage in another task on top. However, we discovered an additional task that supports conflict resolution. In two experiments, participants performed a spatial cognitive control task. For different blocks of trials, they either received no instruction regarding eye movements or were asked to maintain the eyes fixated on a stimulus. The additional eye fixation task did not reduce task performance, but selectively ameliorated the adverse effects of cognitive conflicts on reaction times (Experiment 1). Likewise, in urgent situations, the additional task reduced performance impairments due to stimulus-driven processing overpowering cognitive control (Experiment 2). These findings suggest that maintaining eye fixation locks attentional resources that would otherwise induce spatial cognitive conflicts. This reveals an attentional disinhibition that boosts goal-directed action by relieving pressure from cognitive control.

INTRODUCTION

Cognitive control is a basis for human intelligent behavior, as it enables humans to act according to goals even despite strong tendencies for actions conflicting with these goals that are triggered by the environment. Cognitive control is assumed to be severely limited, so that it suffers once humans engage in more than one task simultaneously.[1,2] We falsify this general assumption by showing that engaging in another task can also have the opposite effect: Dual-tasking can relieve pressure from cognitive control by selectively reducing cognitive conflicts.

Cognitive control enables to act according to one's goals and intentions, preventing salient stimuli in the environment to trigger goal-adverse reactions in a bottom-up, stimulus-driven fashion.[3,4] Thus, cognitive control is the basis of overcoming impulsive behaviors by suppressing stimulus-driven action.[3,5–7] The resolution of cognitive conflicts between stimulus-driven and goal-driven action can also be influenced by spatial attention, the mechanisms that prioritize certain locations for visual processing[8–12] and thereby govern the incoming perceptual information giving rise to the conflicts.[3,5,6] For instance, cognitive conflicts arising from distracting stimuli can be ameliorated if spatial attention is focused at the location of a target stimulus that is supposed to guide action.[13]

The brain mechanisms underlying spatial attention are closely linked with the mechanisms for eye movement control.[14,15] Before a saccadic eye movement is made to a location, covert spatial attention (i.e., attention without eye movements) already enhances visual perception at the saccade target location.[14–17] Therefore, it is assumed that the next saccade target is selected by assigning spatial attention resources to its location, which then leads to the improved visual perception.[18,19] This link of attention and eye movements seems to hold also at the neuronal level: stimulating neurons in brain regions for eye movement control[20,21,22] elicits saccades if the stimulation is strong, but improves visual perception at target locations by spatial attention if stimulation is weaker. Saccadic eye movements seem to require spatial attention, but it is less clear whether the same holds true for suppressing saccades and keeping the eyes fixated on a stimulus. We could assume this was the case, since neuronal regions involved in voluntary eye movements also seem to control the fixation of gaze.[23] Thus, keeping the eyes fixated could lock spatial attention resources at the fixated location in order to prevent saccades to another location. This could impact on cognitive control by influencing the encoding of perceptual information that conflicts with current goals. If this is the case, holding a fixation in a speeded task would modulate the slowing down of reactions by the cognitive

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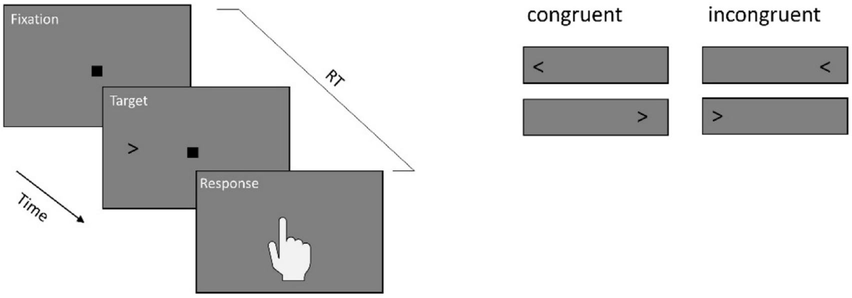

Figure 1. Experimental paradigm in Experiment 1

Each trial started with a fixation stimulus, which was shown for 350, 400, or 500 ms. The order of the fixation durations was randomized. Subsequently, the target stimulus was shown. Participants had to react to the symbolic meaning of the stimulus by pressing the appropriate mouse button. The location of the stimulus was task-irrelevant and could be congruent or incongruent to the pointing direction of the arrow. Depending on the block, participants were either instructed to maintain their gaze on the fixation stimulus during the trial (fixation condition) or received no instruction regarding eye movements (no-fixation condition).

conflict. In urgent situations, stimulus-driven action can overpower goal-directed (intention-driven) action.[24,25] For an antisaccade task, in which participants are instructed to perform a saccade away from an onset target that would usually capture the gaze,[26–29] as well as for manual tasks, it could be shown that urgency opens up a time window in which irrelevant (spatial) stimulus information dominates the response.[24,25] So, if holding a fixation affects the encoding of stimulus information, holding fixation in an urgent situation should modulate the strength of the stimulus-driven response, thus the extent or form of the performance impairment due to the cognitive conflict.

Here, we show that keeping the eyes fixated not only influences the encoding of perceptual information, but impacts on cognitive processing up to the higher levels controlling action. To this end, we examined how maintaining eye fixation affected performance in a spatial cognitive control task, the Spatial Stroop task.[30–32] In two experiments, participants performed the task either without instructions regarding their eye movements or in a dual-task, with the additional task to fixate a stimulus in the center of the screen and suppress eye movements to the target stimulus (for experimental paradigms see Figures 1 and 2, following studies defining dual-task as two simultaneous tasks requiring the execution and/or suppression of different actions, possibly using different effector systems[14,15,33–35]).

Experiment 1 was a standard Spatial Stroop task. In Experiment 2 the task was extended using the urgency paradigm used by Salinas et al.[25] and Poth.[24] Experiment 2 is thus an urgent Spatial Stroop task.

RESULTS

Maintaining an eye fixation improves the resolution of spatial cognitive conflicts

Both experiments were preregistered before data collection on the Open Science framework (Experiment 1: Open Science Framework: https://osf.io/vnh8a; and Experiment 2: Open Science Framework: https://osf.io/t8a9j).

In Experiment 1, the standard Spatial Stroop[30–32] task, arrows, which point to the left or to the right, were presented either on the left or on the right side of the screen. The participants' task was to respond to the arrow direction by clicking the corresponding mouse button. The presentation location of the arrow, which could coincide with the arrow direction (congruent trials) or deviate from it (incongruent trials), was irrelevant and to be ignored. Incongruent trials cause a spatial cognitive conflict between the reaction to the symbolic meaning and the reaction to the more salient but task-irrelevant location and therefore lead to slower reaction times.[32] This congruency effect, which is reflected by the difference in performance, i.e., reaction times, between congruent and incongruent trials, quantifies how well cognitive control mechanisms can resolve the conflict between the irrelevant stimulus location and the symbolic meaning of the stimulus for action control. To examine the effect of eye fixations on cognitive control, depending on the block, participants either received no instruction regarding their eye movements, allowing the eyes to move freely, or were asked to keep their gaze on a fixation stimulus in the center of the screen throughout the entire trial and to suppress an eye

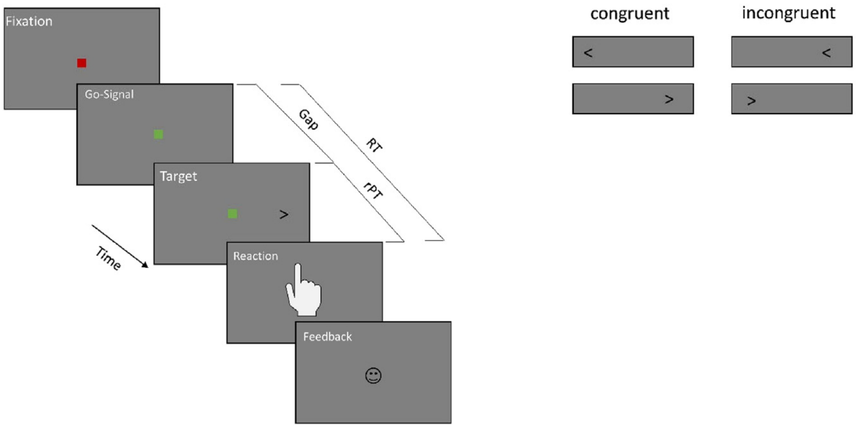

Figure 2. Experimental paradigm in Experiment 2

On each trial, participants fixated a fixation stimulus (350, 400, 500 ms). Its color change from red to green served as go-signal and represented the beginning of a 1000 ms deadline, in which the response had to be executed. After a variable gap duration (0–950 ms), the target stimulus was presented. When the gap was short, the urgency was low and enough time for planning and executing the response was left. Longer gaps entail higher urgency because only little time until the deadline is left. The stimulus was an arrow, pointing to the left or to the right. The location of the stimulus could be congruent or incongruent to the direction, but was task-irrelevant, since the correct response was determined solely by the direction of the arrow. Participants had to press the mouse button which was matching the symbolic meaning of the stimulus. After the reaction, a smiling or frowning face gave feedback regarding the timing of the answer (750 ms). Raw processing time (rPT) constitutes the reaction time (RT) minus the gap duration. As in Experiment 1, there was a fixation condition and a no-fixation condition.

movement to the target stimulus that appeared to the side. Performance comparisons between these block types should provide information about the relationship between eye fixations and cognitive control.

As a manipulation check, the relative frequency of saccades after target onset was calculated and compared between the two fixation conditions. In the no-fixation condition participants performed saccades significantly more frequently (7148 saccades (96.42% of trials) in the no-fixation condition, 2247 (54.29% of trials) saccades in the fixation condition, paired samples Wilcoxon test, $V = 276$ with $p < 0.001$). Also, the latencies of executed saccades differ significantly (paired samples Wilcoxon test, $V = 6$ with $p < 0.001$) between the fixation conditions with higher latencies in the fixation condition ($Md = 618.0$ ms) compared to the no-fixation condition ($Md = 186.5$ ms). The individual number and proportion of saccades are shown in the supplemental information (SI; see Tables S1–S3). Participants' mean Euclidean distance of the final position of the first saccade to the target is on average $M = 5.72°$ visual angle in the fixation condition and $M = 2.45°$ in the no-fixation condition. This difference is significant (paired samples Wilcoxon test, $V = 9$ with $p < 0.001$). The distribution of the saccade landing positions can be seen in Figure 3. Thus, it can be assumed that participants in the no-fixation condition perform saccades in the direction of the target, whereas in the fixation condition they successfully keep their gaze on the fixation stimulus.

If an overt shift of attention, i.e., an eye movement to the target stimulus, is necessary for performing the Spatial Stroop task correctly, the performance should differ between the fixation blocks in terms of accuracy, RT or both. If keeping the eyes fixated locks spatial attention resources at the fixated location this additional task could influence cognitive control, here reflected by the congruency effect, by influencing the encoding of perceptual information that conflicts with current goals. If the addition task of holding a fixation influences the resolution of spatial cognitive conflicts, the congruency effect should differ between the block types. Experiment 1 investigated the influence of maintaining a fixation on the cognitive control of actions by comparing the performance in a standard Spatial Stroop task between blocks with free eye movements and blocks with an additional fixation task. The results show that the task of fixating the stimulus did not affect reaction time or general performance. Neither the reaction time nor the accuracy (proportion of correct answers) differed between the blocks. A covert shift of attention seems to be sufficient to assess stimulus identity and react appropriately. In both conditions, a congruency effect was found for the accuracy as well as for the reaction time (repeated measures ANOVA, $F[1, 20] = 29.09$ with $p < 0.001$ and

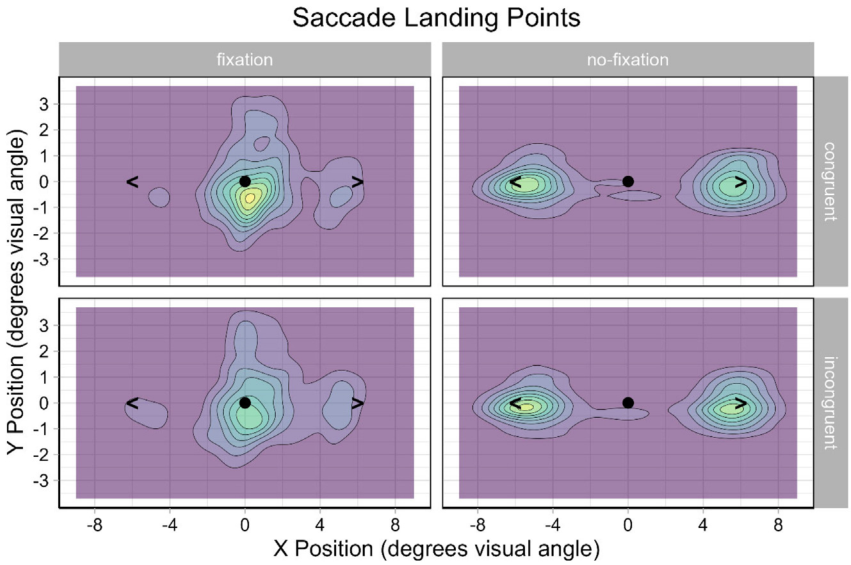

Figure 3. Saccade landing positions support correct execution of fixation task in Experiment 1

The plots show the distribution of the saccade landing positions of the first saccade after target onset on the screen. In the fixation condition the majority of saccades is executed around the fixation stimulus, while in the no-fixation condition saccades were executed to the target positions.

generalized $\eta^2 = 0.21$ for accuracy and $F[1, 20] = 52.97$ with $p < 0.05$ and generalized $\eta^2 = 0.03$ for reaction time). At the same time, the results reveal that the fixation task improved the resolution of the spatial cognitive conflict in the Spatial Stroop task. When suppressing a saccade to the target stimulus, participants were better at ignoring the irrelevant location of the stimulus and performing the goal-directed action to the symbolic meaning. The congruency effect, which shows the difference in reaction times between congruent and incongruent trials and therefore reflects the interaction effect of the ANOVA performed, was smaller in the fixation condition than in the condition in which the eyes were free to move (paired t-test, $t(20) = 2.23$ with $p < 0.05$ and $d = 0.49$; see Figure 4).

To examine effects of inter-individual differences in the proportion of saccades executed on the effect of the fixation, we computed correlation analyses that examine the relationship between participants' proportions of saccades executed and the magnitude of the congruency effect. However, these correlations were not significant ($t = 1.13$, $p = 0.264$ for the fixation condition and $t = -1.24$, $p = 0.218$ for the no-fixation condition).

The results suggest that tying spatial attention by holding a fixation, improves the resolution of spatial cognitive conflicts by simplifying to ignore irrelevant stimulus features and focus on task-relevant stimulus features, reflected by the reduced congruency effect in the fixation condition.

One might speculate that the steeper increase of reaction times in incongruent trials in the no-fixation condition compared with the fixation condition was due to a response-response conflict.[37,38] For the no-fixation condition, participants mostly performed two responses, namely a saccade in the direction of the target and the manual keypress corresponding to the direction of the arrow. In the incongruent condition, this leads to a conflict between the direction of the saccade and the spatial location of the manual keypress. In the fixation condition, on the other hand, no saccades were usually executed, so that no conflict arose between the responses. To test for this, we computed a 2 x 2 ANOVA of the saccade direction and the target direction on the reaction times in Experiment 1. If the effect were to be due to response-response incongruence, there should be a significant interaction of the two variables on reaction time. However, this is not the case ($p = 0.46$).

Maintaining an eye fixation ameliorates adverse effects of urgency on cognitive control

In Experiment 2, the urgent Spatial Stroop task, urgency was evoked by limiting the time available for responding to the target stimulus. This was done by setting a response deadline of 1000 ms.[24] The response

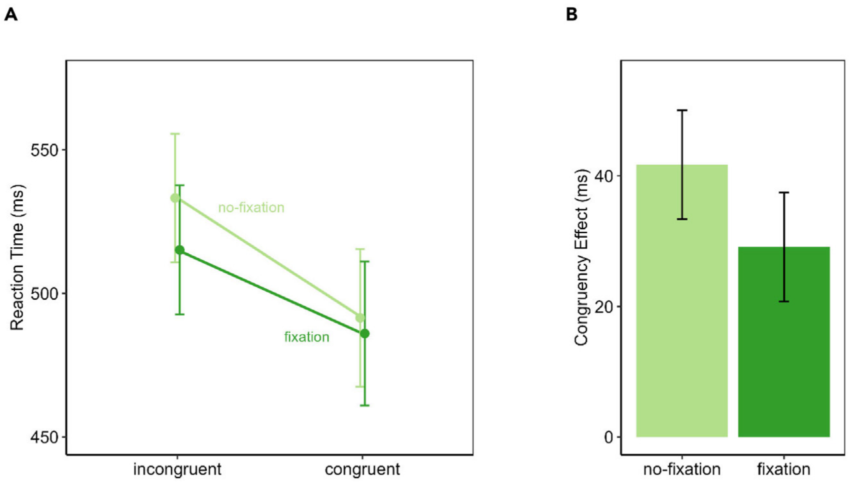

Figure 4. Maintaining an eye fixation improves the resolution of spatial cognitive conflicts

(A) shows the mean reaction time in ms in the congruent and the incongruent condition for the no-fixation and the fixation block. The reaction time is higher in the incongruent than in the congruent condition. In addition, the difference in the reaction times between these conditions (congruency effect) is higher in the no-fixation block. (B) shows the mean congruency effect in ms for the no-fixation and the fixation condition. The fixation task facilitated the resolution of the spatial cognitive conflict, so the congruency effect is smaller in the fixation condition than in the no-fixation condition. Error bars indicate the 95% confidence interval for within-designs.[36]

interval was initiated by a Go signal, a color change of the fixation stimulus. A variable gap (0–950 ms; 0, 100, 200, …, 900, 950 ms) was introduced after the Go signal and before presentation of the target stimulus. The length of the gap reflects the degree of urgency. During the gap, the pressure to respond increases, while the correct response is still unknown due to the missing stimulus. If the gap is long, there is little time left to perceive the upcoming target stimulus, if necessary resolve the cognitive conflict, and initiate a response. In these trials, the urgency should be high. If the gap duration is short, the urgency should be low.

As in Experiment 1, the relative frequency of saccades after target onset was calculated and compared between the fixation condition and the no-fixation condition as a manipulation check. The participants performed significantly more saccades in the no-fixation condition (5579 saccades [60.71% of trials] in the no-fixation condition, 2990 saccades [35.64% of trials] in the fixation condition, paired samples Wilcoxon test, $V = 21$ with $p < 0.05$). The saccade latencies also differ between the fixation conditions ($Md = 361.0$ ms for the fixation condition, $Md = 226.5$ ms for the no-fixation condition; paired sample Wilcoxon test, $V = 0$ with $p < 0.05$). The individual number and proportion of saccades as well as the latencies are shown in the SI (see Tables S4–S6). The distribution of the landing positions of the first saccade after target onset is shown in Figure 5. The average Euclidian distance from this landing position to the target position is $M = 5.11°$ in the fixation condition and $M = 4.04°$ in the no-fixation condition, showing a significant difference (paired samples Wilcoxon test, $V = 0$ with $p < 0.05$). Accordingly, it can be assumed that saccades in the no-fixation condition were executed in the direction of the target, whereas saccades in the fixation condition were executed rather around the fixation stimulus.

For each trial, the raw processing time (rPT) was calculated as the time interval between the appearance of the target stimulus and the response (rPT = reaction time−gap duration). Thus, the rPT represents the amount of time that was available to perceive the target, process it, and execute the response. A tachometric function, a psychometric function representing the accuracy as a function of the rPT, was then plotted for the congruency conditions and for the fixation and no-fixation condition, respectively. For rPTs from −200 to 1000 ms the average proportion of correct answers was calculated for a running bin of 1 ms. As shown as the smooth curves in Figure 6, using the loess-function of R (span parameter 0.2), the performance was then locally regressed on the rPT bins. For both fixation conditions, there was a qualitative difference between the tachometric function of the congruent and that of the incongruent condition (replicating results of Poth[24]). In the congruent condition, the performance was initially at chance level, but increased monotonically from an rPT of about 150 ms onward, transitioning to an asymptote at near-perfect performance. In

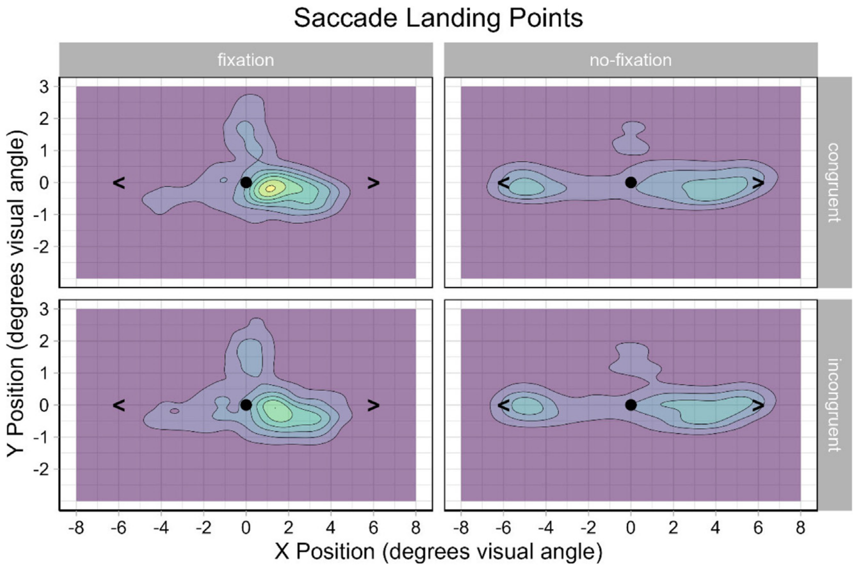

Figure 5. Saccade landing positions support correct execution of fixation task in Experiment 2

The plots show the distribution of the saccade landing positions of the first saccade after target onset on the screen. In the fixation task the majority of saccades is executed around the fixation stimulus, while in the no-fixation task saccades were executed mostly to the target positions.

the incongruent condition, on the other hand, the performance also started at chance level, but dropped clearly below chance level for an rPT around 250 ms. After this drop the performance also increased monotonically into an asymptote (see Figure 6).

As preregistered, we compared the minima of the incongruent tachometric functions for the fixation conditions. The comparison of the minima shows a lower minimum in the no-fixation condition (minimum proportion correct: 20.41%) compared to the fixation condition (minimum proportion correct: 23.92%). However, this difference is not statistically significant (permutation test with $p = 0.152$). Thus, regarding the minima, there was no evidence that maintaining eye fixation affected how stimulus-driven action overpowered goal-directed action. Importantly, the compound measure provided by the minima of the tachometric functions conflates the different parameters of the functions that have been postulated as distinct measures for specific cognitive operations by Salinas et al.[25] Thus, analyzing the minima would conceal potential differences between the fixation and no-fixation conditions, if these differences only affected a specific cognitive operation, as assessed by a specific parameter of the tachometric functions. For this purpose, going beyond the preregistration, the incongruent curves were plotted using the model proposed by Salinas et al.[25] in which the performance is plotted over the running 1ms rPT bins using two combined logistic functions. The first, left logistic function runs downward and is followed by a second, right logistic function that runs upward. The composite functions thus contain four parameters, the inflection point of the left curve as well as that of the right curve and the slope coefficient of the left as well as the right curve.

When directly comparing the two incongruent curves, the drop of the performance under chance level seemed to be steeper in the no-fixation condition than in the fixation condition (see Figure 7). Comparing the parameters of the two curves, it can be seen that the parameters for the point of inflection of the left curve (parameter CL; at a rPT of 235.71 ms for the fixation condition, at a rPT of 182.33 ms for the no-fixation condition; permutation test with $p < 0.05$), the point of inflection of the right curve (parameter CR; at a rPT of 298.52 ms for the fixation condition, at a rPT of 320.16 ms for the no-fixation condition; permutation test with $p < 0.01$), and the slope of the right curve (parameter DR; 40.05 for the fixation condition, 30.33 for the no-fixation condition; permutation test with $p < 0.05$) differ significantly between the two conditions. Similarly, the width of the drop, defined as the distance between the left and the right point of inflection, differs significantly between the fixation conditions (62.81 ms for the fixation condition, 137.82 ms for the no-fixation condition; permutation test with $p < 0.001$). The slope of

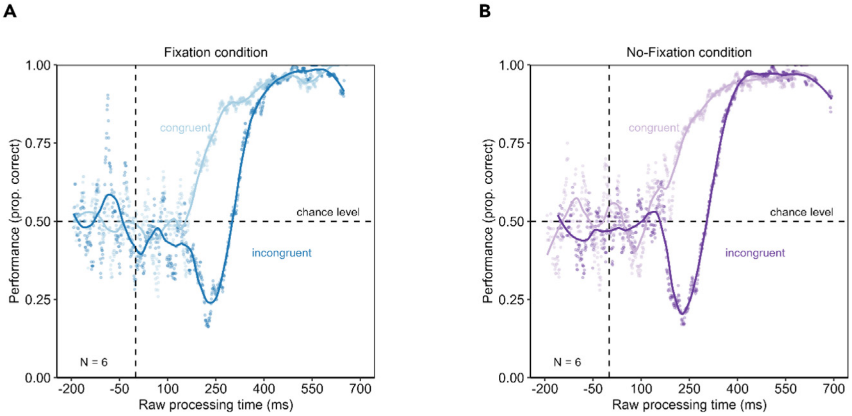

Figure 6. Maintaining an eye fixation ameliorates adverse effects of urgency on cognitive control

The tachometric functions show the performance as a function of the rPT for the congruent and incongruent conditions of the aggregate participant for the fixation condition (A) and for the no-fixation condition (B). In the incongruent condition high urgency led to a drop in performance under chancel level before the performance recovered and increased into an asymptote. In contrast, in the congruent condition the performance directly increased with increasing rPT.

the left curve also differs, but the difference barely misses the significance level (parameter DL; 66.07 for the fixation condition, 4.1 for the no-fixation condition; permutation test with $p = 0.056$). Nevertheless, descriptively the slope of the curve tends to be steeper in the no-fixation condition. This indicates that the task of maintaining an eye fixation and suppressing intuitive eye movements attenuates the adverse effects of urgency on cognitive control.

To rule out the possibility that the effect of the steeper slope in the no-fixation condition may be due to the earlier drop in performance below chance level in the fixation condition, we compared mean performance in the 0 to 150 ms rPT time period between the fixation and no-fixation condition. This difference was not significant (permutation tests for three time bins 0–50 ms, 50–100 ms, and 100–150 ms, all $p > 0.05$). Thus, the earlier drop seems to be due to noise in the data, as it is evident in the tachometric functions based on the data points shown.

Also, the congruent functions were plotted according to the model of Salinas et al.[25] using a simple logistic function. However, when comparing the curve parameters between the fixation and no-fixation condition, there was no significant difference between the conditions for either parameter, the slope as well as the inflection point (all permutation tests for all parameters $p > 0.30$).

DISCUSSION

The present study aimed to investigate the influence of holding a fixation on cognitive control in a spatial cognitive control task, the Spatial Stroop task. Therefore, in two experiments, performance in this task was compared between a block without instruction regarding eye movements and a block with a fixation task in which eye movements to the peripheral target had to be suppressed. In the Spatial Stroop task, a spatial cognitive conflict arises between the location of a stimulus and its symbolic meaning. The first experiment showed that the general performance in a standard Spatial Stroop task did not differ between the two fixation conditions in terms of reaction times or accuracy. The congruency effect, more precisely the difference in reaction times between congruent and incongruent trials, however, was significantly smaller in the blocks in which the additional fixation task was given than in blocks without eye movement instruction. The results imply that the additional task of holding a fixation and suppressing an eye movement does not affect performance per se, but selectively facilitates the resolution of the spatial cognitive conflict.

In the second experiment, the task was extended using an urgency paradigm.[24,25] The results of the urgent Spatial Stroop task replicated basic findings regarding the influence of urgency on cognitive control. In both fixation conditions, high urgency in a certain time window led to a dominance of the salient but task-irrelevant location of the stimulus and thus to a drop in performance. However, these adverse effects

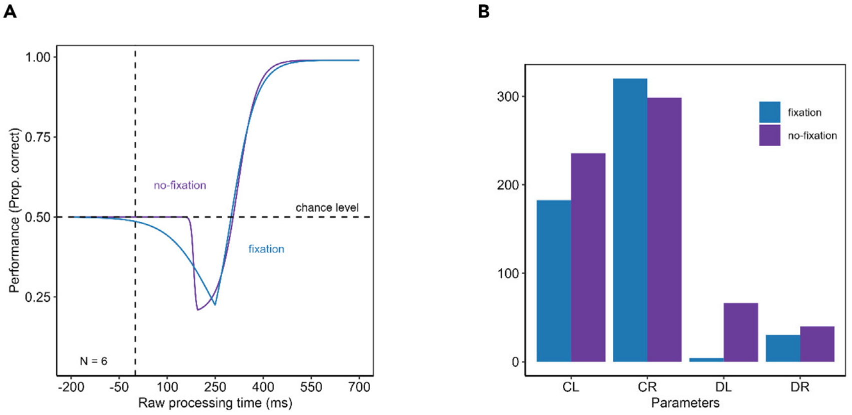

Figure 7. Comparison of the incongruent functions

(A) shows the incongruent curves of both fixation conditions fitted using the model of Salinas et al.[25] (B) shows the plotting parameters of the two sigmoidal curves compared between the fixation conditions. Parameters CR and CL describe the points of inflection for the right (CR) and the left (CL) sigmoidal curve. Parameters DR and DL describe the slopes for the right (DR) and left (DL) sigmoidal curve.

of urgency occurred attenuated when fixation was held simultaneously. This shows that holding a fixation improves the resolution of the spatial cognitive conflict in the Spatial Stroop task.

The second experiment illustrates that the improved resolution of the cognitive conflict does not result from a mere improvement in cognitive control. Instead, it suggests that the improvement results from a deteriorated processing of the salient but irrelevant stimulus dimension, namely the location of the stimulus. The drop in performance does not differ in magnitude between fixation conditions, but it tends to differ in steepness. In the fixation condition, the drop is less steep. The steepness here reflects the processing speed of the irrelevant stimulus location, meaning that in the fixation condition the processing speed of the location was reduced. This suggests that holding the fixation impairs processing of the stimulus location, which in turn reduces interference and facilitates conflict resolution. This may be explained by the allocation of attention (cf. Bundesen et al.[39]; Desimone & Duncan[10]). Holding a fixation could lead to the allocation of spatial attention to the fixation location (paralleling the attention allocation for eye movement control, see Schneider[40]; Wischnewski et al.[41]). Thus, if fixation of the eyes locks a high proportion of the processing capacity at the location of fixation, the processing capacity and thus the processing speed of the target in the periphery is reduced (cf. Bundesen[39]). This reduces the chance for encoding the perceptual information that conflicts the task-related goal, explaining the reduced cognitive conflict.

However, it is assumed that the allocation of attention happens based on the processing of the entire object. So, the reduction of allocated attention should reduce performance in general. Thus, the fact that only the congruency effect is affected here, i.e., that there is an asymmetry in the processing of the stimulus location and the symbolic meaning of the stimulus, requires additional assumptions. The processing of locations in space is closely related to eye movement control. Eye movements and fixation holding as well as location processing are controlled by spatially organized systems such as priority maps. Priority maps are topographic maps of space in which all objects in a visual scene are represented.[42] The priority of an object is determined by its saliency as well as the relevance of the object.[42] Priority maps explain how attention selects the next target location for saccades and prioritized visual perception for attention is selected.[39–41] Thus, both, fixation location and stimulus location, appear to be processed by similar systems. In these experiments due to the additional fixation task the fixation location seems to be prioritized, which in turn reduces the processing of the stimulus location. The symbolic meaning of the stimulus should not be represented in the spatially organized priority map, unlike the location of the stimulus and should therefore rely on different processing mechanisms for object recognition.[43–46] In line with this idea are recent findings that the processing of object location and of object identity for visual recognition proceeds independently and with different temporal dynamics, which could argue in favor of such a difference between underlying processing mechanisms (Poth & Schneider, in prep.). Thus, the visual processing of the symbolic meaning remains unaffected by the prioritization of the fixation stimulus. This asymmetry reinforces that holding a fixation does not improve cognitive control. Instead, it leads to a less prioritized encoding of the stimulus location and therefore reduces the interference in the Spatial Stroop task, leading to a reduced congruency effect.

One may speculate about how the described effects of keeping eye fixation on attention and cognitive conflicts translate to real-world behavior. Interestingly, it has been shown that experts in a sport show longer eye fixations before they initiate a critical movement for the sport (the "quiet eye" phenomenon) and that the fixation duration predicts the success of movement execution.[47,48] Our findings could suggest that the performance benefits associated with maintaining fixation just before action stem from a reduction of spatial cognitive conflicts, if spatial attention was locked at fixation and thus unavailable for eliciting spatial conflicts from the visual periphery (as discussed previously). Thus, taken together, this calls for new research exploring how maintaining eye fixation affects spatial cognitive control in real-world tasks requiring complex sensorimotor actions, such as sports.

We did not find evidence that the differences between the steepness of the drops in performance in the incongruent conditions of the fixation vs. the no-fixation conditions arose from a response-response conflict between saccades on the one hand and our spatially organized manual responses on the other hand. Nevertheless, it remains open whether our results would also occur with a response that is non-spatial in nature. In our experimental paradigms, the spatial cognitive conflict can be assumed to arise due to an automatic activation of the spatially coded response (i.e., left vs. right keypress) by the spatial location of the target stimulus on the screen (i.e., left vs. right side of screen center) that conflicted with the symbolic meaning of the stimulus upon which the response should be based as per task-instruction (i.e., leftward-pointing arrow vs. rightward-pointing arrow, for reviews, see Kornblum et al.,[49] Lu & Proctor[32]). Thus, for non-spatial responses, such as for instance a verbal response, it could be that there was no such spatial cognitive conflict that could be modulated by maintaining eye fixation. This is an interesting question for follow-up research.

Our findings suggest that holding a fixation locks attentional resources at the location of fixation that would otherwise induce spatial cognitive conflicts. In this way, maintaining a fixation leads to an attentional disinhibition and thereby relieves pressure from cognitive control. Thus, the results of the study show that brain mechanisms for eye movement control affect not only visual perception but also ultimately higher cognitive processes for intentional action control. Thus, the results reveal a central role of eye movements for, at first glance, unrelated aspects of intelligent human behavior.

Limitations of the study

Following our explanation of attentional disinhibition of the spatial position, the results of our study are probably limited to spatial conflicts only. For other types of cognitive conflict that are not elicited by the salient spatial position of the stimulus, the effect of the additional fixation task might be different. Instead, it can be suggested that another additional task that targets processing resources shared with the salient and irrelevant stimulus information evoking the conflict leads to an attentional disinhibition at a different level. However, further research is needed to confirm this assumption.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.107520.

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AUTHOR CONTRIBUTIONS

A.K. and C.P. designed the study, A.K. programmed the study and collected the data, A.K. and C.P. analyzed the data, A.K. and C.P wrote the manuscript, C.P. supervised the research.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Datasets	this study	Open Science Framework (RRID:SCR_003238): https://osf.io/w8ntu/
Software and algorithms		
R (Version 4.1.0)	R Core Team[50]	R Project for Statistical Computing (RRID:SCR_001905): https://www.R-project.org/
pwr-package	Champely et al.[51]	https://CRAN.R-project.org/package=pwr
MATLAB (Version R2014b)	MATLAB R2014b, The MathWorks, Inc., Natick, Massachusetts, United States.	MATLAB (RRID:SCR_001622): https://de.mathworks.com/
Psychtoolbox 3	Brainard et al.[52] Kleiner et al.[53]	Psychophysics Toolbox (RRID:SCR_002881): http://psychtoolbox.org/
Eyelink toolbox	Cornelissen et al.[54]	http://psychtoolbox.org/docs/EyelinkToolbox

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Anika Krause (anika.krause@uni-bielefeld.de).

Materials availability

This study did not generate new unique reagents.

Data and code availability

Data have been deposited on the Open Science Framework (Open Science Framework: https://osf.io/w8ntu/) and are publicly available as of the date of publication. All original code has been deposited on the Open Science Framework (Open Science Framework: https://osf.io/w8ntu/) and is publicly available as of the date of publication. Any additional information required to reanalyze the data reported in this work paper is available from the lead contact upon request.

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

Human participants

Experiment 1 was performed by 24 participants. Three participants were excluded because they showed a performance under chance level in at least one condition. Accordingly, the data of 21 participants were analyzed (18 female, 3 male; aged 18 to 31 years, *M* = 23.95, *Md* = 23.5, *SD* = 3.51). Experiment 2 was performed by 6 participants (3 female, 3 male; aged 23 to 34 years, *M* = 30.86, *Md* = 31, *SD* = 3.06).

All participants had normal or corrected-to-normal vision and were native German speakers. All participants gave written informed consent before participating. Both experiments followed the ethical regulations of the German Psychological Society (DGPs) and were approved by Bielefeld University's ethics committee.

Sample size quantification

The sample sizes for these experiments were chosen in advance. The sample size of Experiment 1 is based on a paired t-test power calculation (significance level .05, power .8) using the pwr-package in R.[51] The sample size of Experiment 2 is based on the studies of Salinas et al.[25] and Poth[24] and the experiment is conceptualized as Small-N-Design.[55,56]

Experimental design

Both experiments were conceptualized as within-Designs, so that all participants completed all conditions. The order of the fixation conditions was indicated by participant number (Experiment 1) or session number (Experiment 2). Within the fixation condition, the possible combinations of all other variables occurred equally often and were presented in randomized order.

METHOD DETAILS

Experimental setup

The experiment was performed in a dimly lit room. Participants viewed the computer screen from a distance of 71 cm. The screen was preheated in order to obtain a stable value for the luminance (parameters based on Poth & Horstmann[57]). The head of the person was stabilized by a chin-and-forehead-rest which ensured a standardized distance to the screen.

The stimuli were presented on a CRT-Monitor of the manufacturer View Sonic (Brea, California, USA; model Graphics Serie G90fB; 36 cm x 27 cm) with a refresh rate of 100 Hz and a resolution of 1024 x 768 pixels. The screen was controlled by a graphics card of the type GeForce GTX 970 (driver version 344.48, NVIDIA, Santa Clara, California, USA). The experiment was controlled by the Psychtoolbox3[52,53] and the Eyelink toolbox[54] in MATLAB, version R2014b (The MathWorks, Natick, Massachusetts, USA). The eye movements of the participants were recorded by a video-based and tower-mounted Eyetracker (EyeLink 1000, SR Research, Ontario, Canada) with a measuring rate of 1000 Hz. The Eyetracker was set with a 9-point grid calibration and recorded the participant's right eye. Additionally, a wired computer mouse was used for collecting the participants' responses.

All stimuli in the two experiments were presented in front of a grey background (RGB = 128, 128, 128). As fixation stimulus a square (0.5° visual angle) was presented in the center of the screen. In Experiment 1 the fixations stimulus was black (RGB = 255, 255, 255; <1 cd/ m^2), in the second experiment it was red (0.5° visual angle; RGB = 175, 0, 0; 7.35 cd/ m^2). As target stimuli served black arrows (0.5° visual angle; RGB = 255, 255, 255). The participants task was to indicate whether the presented target stimulus pointed to the left (<) or to the right (>). Both signs were written in font Arial in font size 12 (RGB = 255, 255, 255; <1 cd/ m^2). The arrows could be presented either on the left or on the right side of the screen on a horizontal line and with a distance of 6° visual angle to the center. In the congruent condition the arrow was presented on the side of its pointing direction while it was presented on the other side in the incongruent condition.

In Experiment 2 a green square (0.5° visual angle; RGB = 0, 70, 0; 7.30 cd/ m^2) was used as Go-Signal. In addition, visual feedback about the timeliness of the answer was included in the experiment. The feedback about the timing of the answer consisted of a smiling face (RGB = 255, 255, 255; <1 cd/ m^2) for an answer within the interval or a frowning face (RGB = 255, 255, 255; <1 cd/ m^2),) for an answer that was outside the interval. The feedback stimuli were presented in the center of the screen.

Procedure

Experiment 1 consisted of four blocks with 200 trials each, 800 trials in total. Before each block, 24 practice trials were presented. The procedure of an experimental trial is illustrated in Figure 1.

An experimental trial started with the presentation of the fixation stimulus for 350, 400 or 500 ms. Afterwards, the target stimulus appeared and the participant pressed the button, which matched the pointing direction of the arrow independent of its location of presentation. In two of the blocks, the participants additional task was to fixate the fixation stimulus for the whole duration of the trial (fixation blocks). In the two no-fixation blocks there was no instruction regarding the eye movements, so that the eyes could be moved freely. The order of the blocks was quasi-randomized. The participants were assigned to the ABBA or BAAB design based on their participant number. All combinations of the fixation durations, pointing directions of the target, and congruency conditions occurred equally often and in randomized order.

Experiment 2 included five sessions with each 1056 trials in eight blocks with each 132 trials, resulting in 5280 trials in total. The first two blocks of the first session were used as practice trials (264 trials). Figure 2 illustrates an experimental trial. Each trial started with the presentation of the square as fixation stimulus in the center of the screen for 350, 400 or 500 ms. The color change of the fixation stimulus from red to green served as Go-Signal and marked the beginning of the 1000 ms answer interval. After a variable gap interval from 0 ms to 950 ms (0, 100, 200, …, 900, 950 ms) the target was presented. The longer the gap duration, the higher was the degree of urgency, since a long gap leaves little time to select and execute the correct response to the stimulus. If the target stimulus pointed to the right side the participant had to press the right mouse button. Analogous, the participant had to press the left mouse button if the arrow pointed to the left. The target location was task-irrelevant and should be ignored. After the target disappeared, the feedback about the timing of the response was presented for 750 ms. If the participant responded within the 1000 ms interval, a positive feedback, i.e. a smiling face, was presented. If the response was too late, a sad looking face appeared.

The experiment consisted of two different block types, which were both presented four times. In fixation blocks, the participants had to fixate the fixation stimulus throughout the entire trial and were instructed to suppress eye movements to the upcoming target stimulus. In no-fixation blocks the eyes could be moved freely, here the participants did not receive any instruction regarding their eye movements. The order of the blocks was quasi-randomized. Each participant did all blocks, depending on the session they were assigned to the ABBAABBA or BAABBAAB design. All combinations of the fixation durations, gap durations, pointing directions of the target, and congruency conditions occurred equally often within the blocks and in randomized order.

QUANTIFICATION AND STATISTICAL ANALYSIS

Data and analysis code are available on the Open Science Framework (Open Science Framework: https://osf.io/w8ntu/). Data were analyzed using R (4.1.0, https://www.R-project.org/).[50]

For the analysis, the practice trials (Experiment 1: 16 trials before each block, in total 64 trials; Experiment 2: first two blocks of the first session, in total 264 trials) were excluded. Additionally, in the blocks with fixation, all trials in which the fixation was broken were excluded. Before that, as a manipulation check we compared the proportion of executed saccades between the fixation and the no-fixation condition using a paired Wilcoxon signed rank test for both experiments. As well the latency of the first saccade after target onset and the mean Euclidian distance of the landing position of this saccade to the target position were compared between the fixation conditions with a paired Wilcoxon signed rank test. In addition, we plotted the landing position of the saccades as a 2D density plot for each congruency condition and each fixation condition. For all these analyses we excluded microsaccades, defined as saccades with an amplitude smaller than 1 dva.[58] As well, for Experiment 1 trials with reaction times that differed by more than two standard deviations from the participant's mean reaction time in the corresponding condition were not included in the analysis. In addition, in Experiment 1, unfortunately, one set of eye movement data, the data set of participant 21, was incomplete, so the data of this person could not be used for the analysis of gaze behavior.

Accuracy was computed as the proportion of correct answers. For the analysis of the reaction time in Experiment 1, trials in which the wrong answer was given were excluded. Similarly, trials with reaction times that differed by more than two standard deviations from the participants' mean reaction time in the corresponding condition were not included in the analysis. Reaction times and accuracy were compared between the conditions using a repeated measures ANOVA. The congruency effect was computed as the difference in RT between congruent and incongruent trials and compared using a paired t-test. The t-test performed is equivalent to the interaction effect of the ANOVA previously performed. To test for inter-individual differences regarding the proportion of executed saccades and the effect of these differences on the effect we calculated the correlation between participants' individual congruency-effect and their proportion of executed saccades. In addition, for checking the effect of the response-response conflict we calculated a 2 x 2 ANOVA for the effect of the target direction and the saccade direction on the reaction times in Experiment 1.

The analyses in the second experiment deviated from the preregistered analysis methods by analyzing additional curve parameters beyond the minimum. This method was used because the parameters provide more detailed information about the underlying processes of the effect, while the minima are compound measures influenced by many factors. In Experiment 2, the rPT was calculated for each trial. The rPT is characterized as the difference between the reaction time minus the gap duration. It thus represents the time available for processing the target stimulus and initiating the response. In the analyses, the rPT was treated as an independent variable.[25] Only rPTs from -200 to 1000 ms were used to calculate the tachometric functions. The average proportion of correct answers was calculated for a running bin of 1 ms. Using the loess-function of R (span parameter 0.2), the performance was then locally regressed on the rPT bins to calculate both the congruent and incongruent tachometric functions. Four tachometric functions were plotted, one for each of the two fixation conditions and the congruency conditions. As the data were concordant across all participants, the data analysis was performed on the aggregated data. The minima of the curves were compared using a permutation test. The permutation test locates the original difference of the minima between the fixation and the no-fixation condition in a distribution of effects from a 1000-fold reanalysis of the raw data with a randomized labelling of the conditions. For comparing the parameters of the two incongruent curves, the performance over the running 1ms rPT bins was plotted using the model of Salinas et al.[25] Here two logistic functions are combined, one running downwards followed by a second logistic function running upwards. Permutation tests were calculated as described above to compare the parameters of the sigmoidal curves as well as the width of the performance drop under the chance level between the fixation conditions. Performance in the period from 0 to 150 ms rPT was also compared with a permutation test. Separately for three time bins (0 to 50 ms, 50 to 100 ms and 100 to 150 ms) the difference in mean performance between the fixation and the no-fixation condition was tested for significance. The congruent curves were fitted as simple logistic functions according to the model of Salinas et al.[25] Parameter comparisons between the fixation conditions were performed using permutation tests as for the incongruent functions.

ADDITIONAL RESOURCES

Both experiments were preregistered before data collection on the Open Science framework (Experiment 1: Open Science Framework: https://osf.io/vnh8a; and Experiment 2: Open Science Framework: https://osf.io/t8a9j).