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Differential Interference of Body- and Non-Body-Related Representational Conflicts on Error and Performance Monitoring in Flanker Tasks

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Abstract

The performance monitoring system handles representational conflicts with the goal of reducing errors. What remains unclear is whether and how the representational nature of a stimulus modulates conflict resolution. To deal with this issue, we performed five experiments to measure the degree of cognitive interference occurring in Flanker tasks and tested whether effects induced by body- and non-body-related stimuli may change as a function of task requirements and affect conflict processing. In Experiment1, conflicts elicited by hands/letters were used to activate typical competing responses. In Experiment2, stimuli were perceptually matched for low-level features (e.g., target/flanker contrast). In Experiment3, no-go trials were added to increase conflict load and reveal content-driven effects in inhibitory control. In Experiment 4, the onset of target/flanker competition was set at two different delays to investigate conflict persistence during target processing. Finally, in Experiment5, body- vs non-body-related stimuli were combined to measure content-driven effects underlying conflict resolution. A multi-analysis approach to data was employed, combining linear and Bayesian drift-diffusion models. Results show that body-related representations reduced cognitive interference, a robust effect that was observed across all experiments. These findings suggest that representations related to the body selectively engage the performance monitoring system during conflict processing.

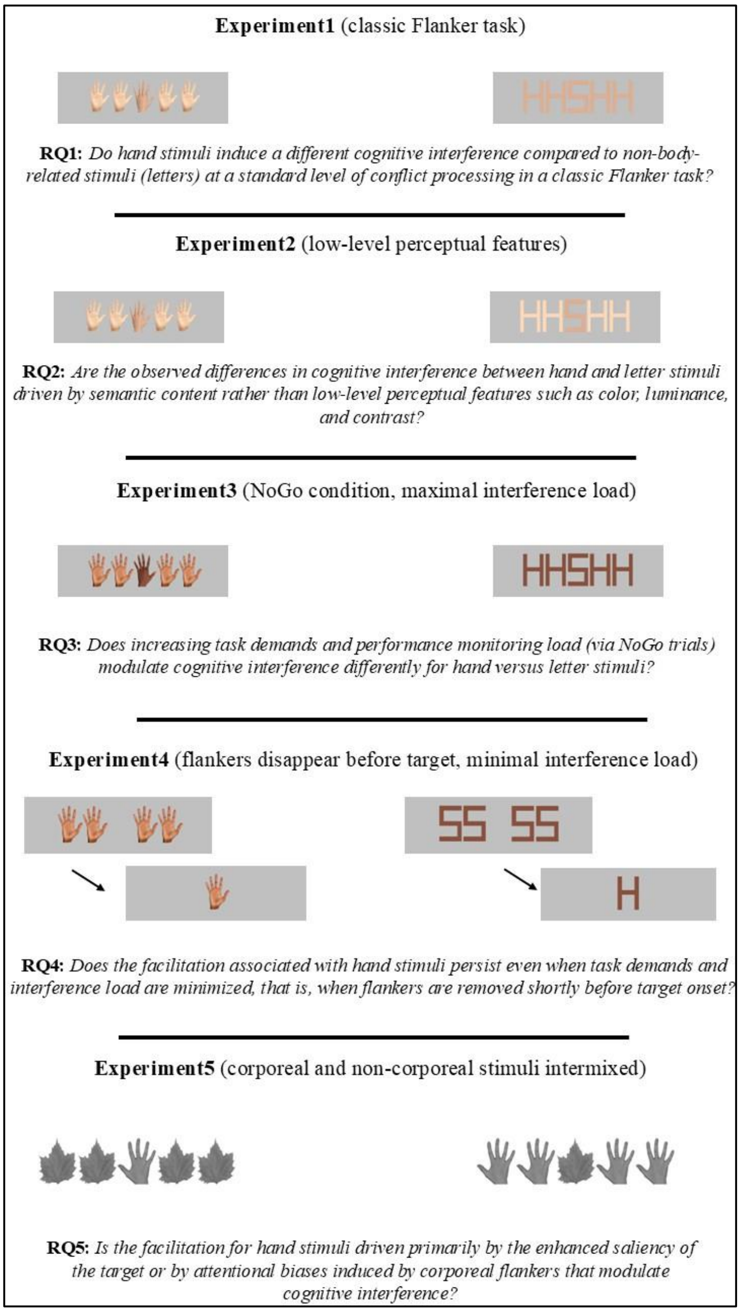
Keywords: Performance Monitoring; Stimulus–Response Representation; Cognitive Interference; Conflicting Stimuli; Cognitive Control; Bayesian Drift-Diffusion Model

Introduction

Cognitive functions support human behavior, allowing for flexible adjustments in response to ever-changing environments. To achieve this adaptation efficiently, highly organized neuro-computational systems are required to avoid errors and thus optimize behavior. A crucial example is the performance monitoring system that keeps track of information processing, detects incongruencies in stimulus–response representations, and contributes to implement selective attention and top-down control [1-3]. Monitoring functions enable online control and regulation of motor behaviors by rapidly activating or inhibiting competing representations and facilitating accurate decision-making. Individuals respond to conflicts and errors via complex computational operations orchestrated by the anterior cingulate cortex (ACC), a functional brain region acting as a hub of a large performance monitoring neural network [4]. When cognitive conflicts are detected, the ACC primes a request for the exertion of top-down control, which contributes to the minimization of errors likelihood in response execution [5].

Evidence coming from conflict-eliciting tasks, such as the Stroop task [6], the Simon task [7], or the Eriksen Flanker task [8], suggest that representational conflicts can be experimentally manipulated by perceptual, semantic, contextual, and individual factors [9-11]. A classic paradigm used to test conflict and error processing is the Letter-Flanker task, in which participants are asked to respond to target stimuli (e.g., a central letter H or S) flanked by task-irrelevant distractors (flankers) that are either dissimilar (e.g., SSHSS or HHSHH; the incongruent condition) or identical (e.g., HHHHH or SSSSS; the congruent condition). In the incongruent condition, two stimulus-response representations are co-activated and compete to trigger the most appropriate motor plan as determined by the task goal. Thus, the mismatch between target and flankers induces motor-perceptual conflict and increases the likelihood of execution errors. In contrast, in the congruent condition, a single representation is activated during information processing, reducing conflict and facilitating the achievement of correct responses [8]. The attentional resources captured by task-irrelevant stimuli during target processing generate the so-called *flanker congruency effect*, a behavioral measure reflecting the cognitive cost of resolving conflicts between incongruent representations relative to congruent ones [12].

Such cognitive interference can vary as a function of various aspects of the task and relevant stimulus-response contingencies, thereby providing additional insight into the functional processing underpinning performance monitoring [13, 14]. Moreover, studies report that the magnitude of interference might depend on representational features that can capture attentional resources and modulate reliance on stimulus properties and semantics to resolve conflicts. This is evident in Flanker paradigms where target/flanker conflicts are activated by affective faces [15, 16], bodies [17, 18], affordable objects [19], caloric food [20], and animals [21]. However, studies using the Flanker task lack a direct comparison between selective stimuli, thus challenging the idea that the processing of cognitive interferences may activate the performance monitoring system based on the different representational content. This research question is particularly pertinent in the field investigating the encoding of body-related representations [22]. Cognitive functions, in fact, are bolstered by integrated representational systems that rely on multimodal sensory and motor signals to develop internal models of bodily states and facilitate individuals' behaviors during actions and social interactions [23]. Corporeal representations, therefore, appear to be selective for the performance monitoring system, supplying the basis for the functional exchange between perceptual, cognitive, and sensorimotor processes, ultimately facilitating successful goal-directed behaviors [24-28]. Notably, paradigms probing conflict and error monitoring in laboratory settings have been reported to elicit behavioral and neurophysiological effects in the administration of tasks activating body representations, such as “fat” or “thin” words in the emotional variant of the Stroop task [29, 30], underweight or overweight body shapes in the Body-Flanker task [18] or virtual arms performing correct or erroneous actions in reaching-to-grasp tasks [31-33]. These findings further emphasize the continuous interplay between performance monitoring and bodily representations during information processing. In the present study, human hands (Exp1-5), capital letters (Exp1-4), and leaves stimuli (Exp5) were used as targets and distractors to explore whether content-driven conflicts affect the performance monitoring system while processing interferences during different Flanker paradigms. Specifically, by manipulating the structural context of tasks we aimed to assess variations of flanker congruency effects derived from the processing of conflicting semantic representations and their impact on behavior. For each stimulus class, we computed a standardized flanker congruency index to allow comparisons of cognitive interference across different representational domains, while controlling for potential influences of low-level visual features (e.g., shape, stimulus complexity) that might bias attentional orienting during conflict resolution. Our explorative hypothesis was that, within the same sample, we would observe a specific pattern of congruency effects reflecting a different sensitivity to body-related compared to non-body-related contents. In line with our previous study [18], indeed, which showed behavioral facilitation when neurotypical participants resolved representational incongruencies involving conflicting bodies in a modified Flanker task, we predicted in the present study that body-related stimuli, rather than non-body-related ones, would facilitate performance monitoring eliciting lesser cognitive interference. In turn, we designed five experimental manipulations. In Experiment1, we employed the classic Flanker task in which congruent or incongruent stimuli flanked the central target. This allowed us to measure the typical interference effect at a standard level of conflict processing when two mutually exclusive response representations are co-activated during task performance. However, since the palm and back of the hand naturally differ in their chromatic characteristics (i.e., the backs are slightly darker than the palms), which may differentially capture attention, in Experiment2 we tested whether the observed effects were content-related by controlling for low-level perceptual features. To this end, we matched the color, luminance, and contrast of hand and letter stimuli to minimize their dissimilarity at the low perceptual level. In Experiment3, we introduced a NoGo condition with no-go trials randomly interspersed with flanker trials (the go condition), to increase task demands and the load of performance monitoring, leading participants to handle interacting sources of conflict, one due to the response mapping between target and flankers, and another due to the activation or inhibition of motor responses (i.e., the conflict level relating to the need to withhold a frequent or preponderant response). Conversely, in Experiment4, we aimed to reduce task demands and test congruency effects under minimal interferential load, by presenting flankers that disappeared either 200 or 50 ms before target onset. Therefore, Experiments3 and 4 can be conceptualized as opposite manipulations along an information-processing continuum, Experiment3 representing the more demanding condition and Experiment 4 the simpler one, with Experiments1 and 2 occupying intermediate stages of difficulty according to the cognitive load required to process simultaneous levels of conflict. Finally, in Experiment 5, corporeal (i.e., hands) and non-corporeal representations (i.e., leaves) were intermixed to test whether the expected facilitation would depend more on the enhanced saliency of target processing or, alternatively, on an attentional bias driven by the flankers that modulate cognitive interference (Fig.1).



Experiment1 (classic Flanker task)

RQ1: *Do hand stimuli induce a different cognitive interference compared to non-body-related stimuli (letters) at a standard level of conflict processing in a classic Flanker task?*

Experiment2 (low-level perceptual features)

RQ2: *Are the observed differences in cognitive interference between hand and letter stimuli driven by semantic content rather than low-level perceptual features such as color, luminance, and contrast?*

Experiment3 (NoGo condition, maximal interference load)

RQ3: *Does increasing task demands and performance monitoring load (via NoGo trials) modulate cognitive interference differently for hand versus letter stimuli?*

Experiment4 (flankers disappear before target, minimal interference load)

RQ4: *Does the facilitation associated with hand stimuli persist even when task demands and interference load are minimized, that is, when flankers are removed shortly before target onset?*

Experiment5 (corporeal and non-corporeal stimuli intermixed)

RQ5: *Is the facilitation for hand stimuli driven primarily by the enhanced saliency of the target or by attentional biases induced by corporeal flankers that modulate cognitive interference?*

Figure 1. Schematic representation and research questions (RQs) of the study design.

Results

Experiment 1

Reduced flanker congruency effect driven by body-related stimuli

Motor–perceptual conflicts underlying stimulus–response interactions induce less cognitive interference in the Hand-Flanker (HF) task than in the Letter-Flanker (LF) task suggesting that incongruent body-related stimuli (as compared to non-body-related stimuli) may require less resources and facilitated information processing in the response selection stage. An ANOVA over the RTs index indicated that there was a main effect of Task (F(1,23) = 57.587; $p < 0.0001$; $\eta_p^2 = 0.714$), reflecting a reduced compatibility effect for hand stimuli (mean ± SEM: 4.38 ± 0.41 ms) compared to letter stimuli (8.34 ± 0.42 ms). Similarly, analysis of Acc indicated that there was a significant main effect of Task (F(1,23) = 32.933; $p < 0.0001$; $\eta_p^2 = 0.588$), again reflecting a lower interference index for the HF task (6.09 ± 0.78) compared to the LF task (13.42 ± 0.90). An ANOVA over RT/Acc also confirmed that there was a main effect of Task (F(1,23) = 45.795; $p < 0.0001$; $\eta_p^2 = 0.665$), indicating that participants exhibited greater proficiency in resolving the interference involved in the HF task (10.41 ± 1.06) compared to the LF task (21.44 ± 1.11; Fig. 2).

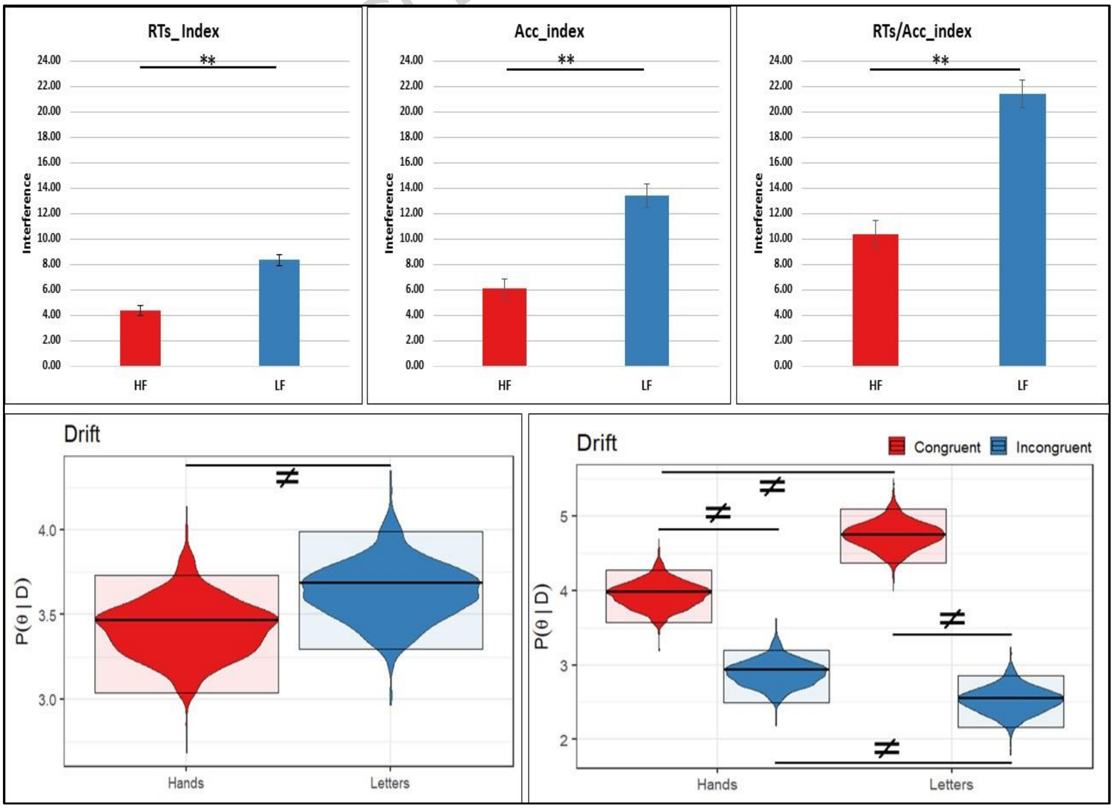


Figure 2. Top: Bar plots representing the interference indices for each dependent variable in the two versions of the Flanker task in Exp1 (HF = Hand Flanker; LF = Letter Flanker). Double asterisks (**) denote comparisons where $p < 0.001$. **Bottom:** Violin plots represent the posterior distribution of drift parameters in the BDDM, box outlines represent the 95% HDI and the darker central horizontal line represents the mode of the posterior distribution. The ≠ symbol indicates differences between conditions.

A complementary analysis was also conducted for all the experiments of the study in which a Bayesian drift-diffusion model (BDDM) was used to capture conflict-related aspects of the time-constrained binary decisions made during task performance [34,35]. Considering the continuous stream of random noise in information processing, this type of model assumes that task-related information accumulates over the course of a trial, leading to a critical decisional threshold activating either a correct or an erroneous response. When one of the two decision boundaries is reached, the corresponding decision triggers motor execution [35]. Several parameters can be estimated for the BDDM: drift rate (uptake of information extracted from stimulus processing per unit of time; the lower the drift rate, the more difficult the task condition); boundary/threshold separation (the amount of information required to decide according to a particular response strategy; liberal strategies are associated with a small distance between thresholds, whereas conservative strategies involve a wide threshold separation); starting point (which indexes any a priori knowledge that biases the decision processes); and non-decision time (the temporal encoding of information processing taken up by other cognitive and motor processing;[34]). In the study, we particularly focus on the drift rate, which is associated with the ability to efficiently accumulate evidence, and threshold separation, which reflects the speed-accuracy trade-off of participants.

Evidence from the BDDM analysis seem to support the facilitation effect driven by hand stimuli (see the Supplementary for the detailed analysis): although participants did not change their decisional strategies based on stimulus content (as indicated by the fact that there were no effects of any independent variable on the boundary parameter), conflict processing might have benefited from the presentation of body-related information. Specifically, there was less difference in drift rates (representing the accumulation of evidence) between the congruent and incongruent conditions in the

HF task compared to the LF task, indicating that participants needed to accumulate more information to reach a decision and handle representational conflict in the case of letter- compared to hand-driven conflicts. Previous evidence highlighted the possibility that flanker congruency effects can be modulated by the (dis)similarity of low-level features between target and flankers [36, 37]. For example, it has been shown that stimulus color might generate pop-out effects facilitating target identification and affecting the interferential processing exerted by distractors [38]. Although in our study stimuli did not result significantly different for perceptual low-level features (e.g., luminance, contrast), given the natural difference in color between the palm and back of hand stimuli (i.e., lighter for the former and darker for the latter), it is plausible that corporeal flankers may have influenced information encoding and altered cognitive interferences. Color dissimilarity was not present for letters, and this may question the evidence of content-specific effects. To test the impact of basic perceptual features on conflict processing, we conducted a control study (Exp2) in which we adjusted the color of the target/flanker combination of letter stimuli to reproduce a similar color difference presented in the hand ones.

Experiment 2

Hand vs Letter conflicts reduce interference regardless of target/flanker color contrast

Body- (i.e., hands) vs. non-body-related (i.e., letters) representations induced distinct levels of interference, confirming findings reported in Experiment1. The analysis revealed a main effect of Task ($F(1,24) = 42.587$; $p < 0.0001$; $\eta_p^2 = 0.641$; Fig. 3) showing that hands stimuli evoked a lesser flanker effect (4.41 ± 0.32) compared to letters (8.76 ± 0.45). For accuracy, it was confirmed the same pattern with the main effect of Task ($F(1,24) = 12.547$; $p < 0.0001$; $\eta_p^2 = 0.343$), in which emerges a greater interference in the LF (4.62 ± 0.63) rather than in HF (8.68 ± 0.85; Fig. 3). Finally, the index measured on the overall performance highlighted the main effect of Task ($F(1,24) = 6.294$; $p < 0.0001$; $\eta_p^2 = 0.528$) and the significant interaction Task x Color ($F(1,24) = 26.933$; $p = 0.0193$; $\eta_p^2 = 0.207$). Post-hoc analysis indicated that brown hands induced a reduced flanker effect (7.61 ± 0.92) rather than pink hands (10.38 ± 1.27; p = 0.0241), pink letters (17.04 ± 1.43; p < 0.001), and brown letters (17.45 ± 1.70; p < 0.001). In the same line, pink hands elicited lower interference rather than both pink (p < 0.001) and brown letters (p < 0.001).

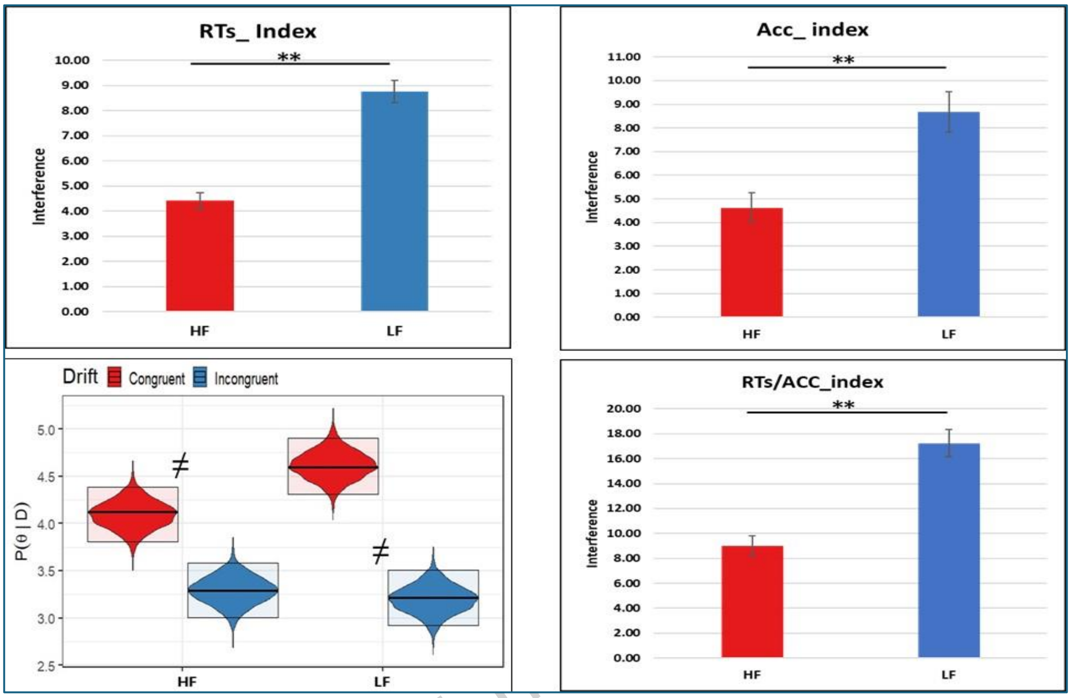


Figure 3. Bar plots representing the interference indices for each dependent variable in the two versions of the Flanker task in Experiment 2 (HF = Hand Flanker; LF = Letter Flanker). Double asterisks (**) denote comparisons where p < 0.001. Violin plots represent the posterior distribution of drift parameters in the BDDM, box outlines represent the 95% HDI and the darker central horizontal line represents the mode of the posterior distribution. The ≠ symbol indicates differences between conditions.

Therefore, even under conditions of perceptual similarity reflecting the target/flanker contrast difference, a lower flanker effect emerged in the HF compared to the LF task. Such an effect was seemingly unrelated to the color dimension. However, when considering the classic dependent variables of the Flanker task (i.e., RTs, accuracy, and the RT/accuracy), congruent letter trials were processed faster and more accurately than congruent hand trials. This suggests that, in the absence of conflict, letters may be encoded more efficiently than hands. Consequently, the larger congruency effect in the letter condition appears largely driven by the facilitation of congruent letter trials. Crucially, however, this facilitation does not extend to incongruent trials: when letters serve as incongruent flankers, they induce stronger interference than hand flankers, as reflected in consistently worse performance for letter-incongruent trials across all measures (all ps < .05; see the analysis on the Supplementary). Additional support comes from the BBDM analysis (see Supplementary) which replicates the pattern observed in Experiment1 and highlights the advantage of corporeal stimuli in enhancing decision-making and response selection. In particular, the BDDM analysis suggests that these differences are related to the stimulus rather than on response processing. Indeed, the exploratory analysis showed that while evidence accumulation is faster for congruent rather than LF trials, this effect is also observable for incongruent compared to congruent trials in the HF task. So, the supposed computational gain in information processing for hand stimuli might be specific in condition of target/flanker competition. Nevertheless, the convergence of evidence between Experiment1 and Experiment2 may reflect contextual manipulations that prioritize motor-response conflict and involve performance monitoring at the same stage of analysis. In the following two experiments, we tested whether the cognitive interference facilitation of hand stimuli extends also to other levels of representational conflicts. Specifically, in Experiment 3, we designed a Flanker-NoGo task where successful performance required attentional control, conflict/error monitoring, and response inhibition for successful performance. In Experiment 4, we used a similar paradigm and manipulated the timing of flankers' onset and offset to decrease the interferential effect of distractors over the target.

Experiment 3

Interference facilitation of body-related representations is not affected by conflict load

In Experiment 3, we tested whether body-related representations improved cognitive interference even when multiple levels of conflict were involved (i.e., conflict between targets and flankers and between go and no-go trials). Overall, the processing of cognitive interferences seems to mirror the results of Experiment 1 and Experiment 2, in which we observed reduced congruency effects associated with hand respect to letter representations. Indeed, the ANOVA over RTs indicated that there was a main effect of Task ($F(1,23) = 19.574$; $p < 0.0002$; $\eta_p^2 = 0.459$), reflecting a stronger interference effect in the LF task (9.43 ± 0.41) compared to the HF task (6.83 ± 0.46). A non-parametric Friedman ANOVA was carried out for accuracy data indicating no significant differences between the conditions ($\chi^2_{(3)} = 4.881$; $p = 0.181$). The ANOVA over RT/Acc, instead, also indicated that there was a significant main effect of Task ($F(1,23) = 9.966$; $p < 0.005$; $\eta_p^2 = 0.302$). This effect was driven by facilitation of the processing of conflicting representations in the case of hand (9.40 ± 0.741) compared to letter stimuli (12.74 ± 0.806; Fig. 4). Further evidence came from the drift diffusion analysis confirming that the congruency effect was greater in the LF task (mode = 1.779, 95% HDI = [1.211, 2.254]) than in the HF task (mode = 0.848, 95% HDI = [0.243, 1.279]). Additionally, the analysis indicated that there was also a main effect of Color ($F(1,23) = 6.665$; $p = 0.017$; $\eta_p^2 = 0.302$), revealing that stimuli depicted in brown (10.33 ± 0.799) induced less interference than those depicted in pink (11.80 ± 0.81).

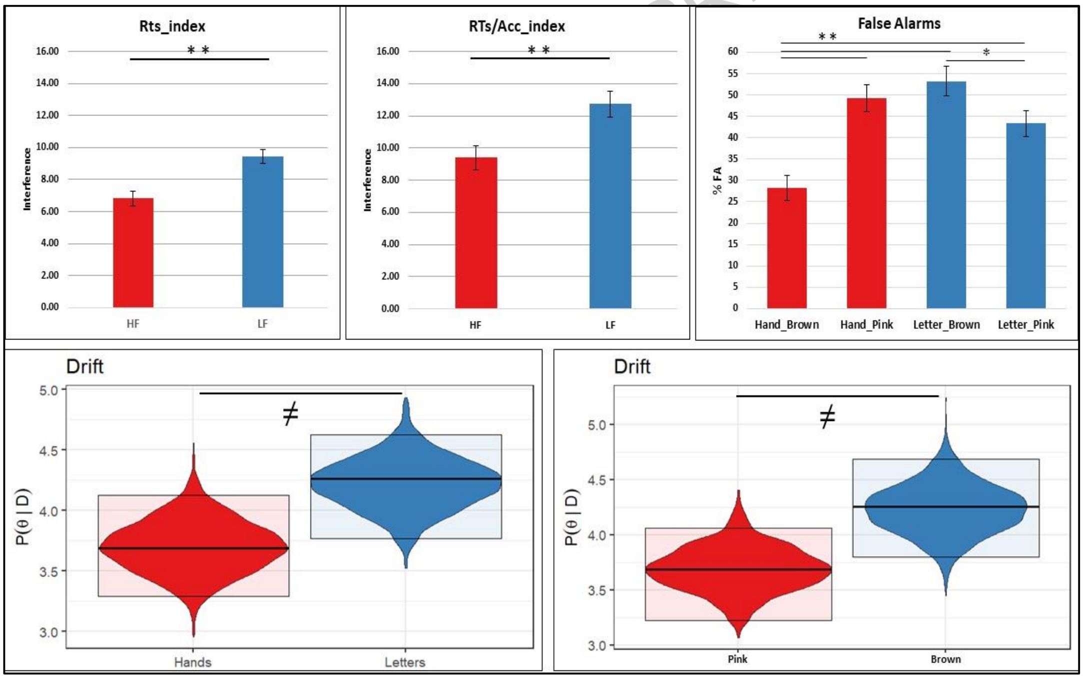


Figure 4. Top left and middle: Bar plots representing the interference indices for reaction times (RTs) and overall performance (RT/Acc) in Experiment 2. **Top right:** bar plot illustrating the proportion of false alarms (FAs) in each task. A single asterisk (*) denotes comparisons where $p < 0.05$; double asterisks (**) denote comparisons where $p < 0.001$. **Bottom:** Violin plots represent the posterior distribution of drift parameters in the BDDM, box outlines represent the 95% HDI and the darker central horizontal line represents the mode of the posterior distribution. The ≠ symbol indicates differences between conditions.

However, the facilitation observed for congruency effects in the HF task does not appear to reflect a cognitive gain in performance monitoring, as was the case in Experiment 1 and Experiment 2. Indeed, we did not observe better overall behavioral performance in the HF task compared to the LF task (see Supplementary Materials). Importantly, we found evidence of facilitation in response inhibition on no-go trials involving hand-related targets. This effect was selective to trials with brown hand stimuli, suggesting that color encoding may have enhanced perceptual and attentional allocation to support conflict processing during response inhibition. Notably, presenting stimuli in brown did not improve inhibitory performance in the LF task, which showed the highest proportion of false alarms (FAs).

In Experiment 4, the distracting strength of flanker representations was manipulated by removing the flankers at one of two randomly-selected latencies prior to the target onset. This way, we aimed to reduce the interfering activation of incongruent distractors during target processing.

Experiment 4

Attenuated representational interference and temporal dynamics of conflict processing

Consistently with the findings of our previous experiments, we observed a reduced congruency effect in the HF task compared to the LF task. The ANOVA over the RTs index revealed a main effect of Task was again observed ($F(1,23) = 22.451$; $p < 0.0001$; $\eta_p^2 = 0.494$), reflecting reduced interference in the HF task (5.31 ± 0.67) compared to the LF task (8.79 ± 0.59). Additionally, there was a main effect of Delay ($F(1,23) = 5.551$; $p = 0.027$; $\eta_p^2 = 0.194$), reflecting a greater flanker effect in the 200 ms delay condition (7.92 ± 0.53) compared to the 50 ms delay condition (6.18 ± 0.43). In line with the results of Experiment 3, a Friedman ANOVA over Acc did not indicate any significant differences between conditions ($\chi^2_{(3)} = 6.425$; $p = 0.491$). Finally, analysis of RT/Acc indicated that there was a main effect of Delay ($F(1,23) = 4.930$; $p = 0.036$; $\eta_p^2 = 0.176$), highlighting less interference in the 50 ms delay condition (7.48 ± 0.50) compared to the 200 ms delay condition

(9.27 ± 0.63), and a main effect of Task (F(1,23) = 9.153; $p = 0.006$; $\eta_p^2 = 0.284$; Fig. 5), reflecting a stronger flanker interference effect in the LF task (10.03 ± 0.73) than in the HF task (6.72 ± 0.80).

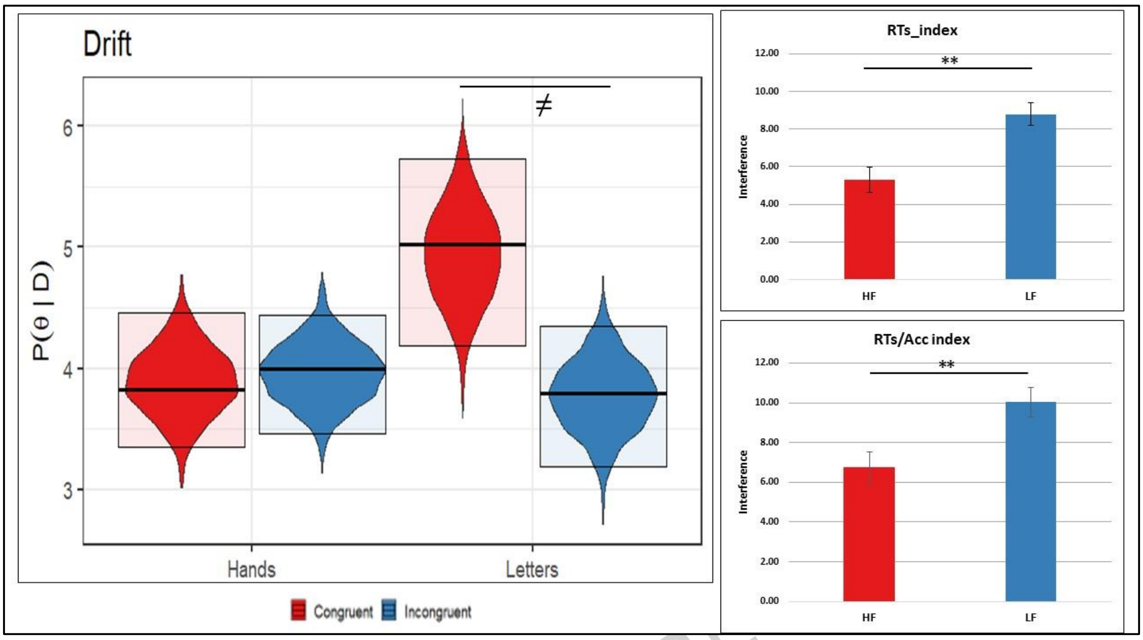


Figure 5. Left. Violin plots represent the posterior distribution of drift parameters in the BDDM for Experiment 4, box outlines represent the 95% HDI and the darker central horizontal line represents the mode of the posterior distribution. The ≠ symbol indicates differences between conditions. **Right.** Bar plots representing the interference indices based on reaction times (RTs; top panel) and overall performance (RTs/Acc; bottom panel). Double asterisks (**) denote comparisons where $p < 0.001$.

Results confirmed that, under conditions of reduced attentional bias induced by distractors, the flanker effect was attenuated for hand representations. The BBDM analysis further revealed that while the LF task exhibited better performance in the congruent compared to the incongruent condition, no flanker congruency effects were observed in the HF task. As a possible explanation, we submit that conflicts arising from hand compared to letter distractors decay more rapidly during information processing, thereby reducing representational interference. This facilitates an exclusive attentional focus on target processing and, in turn, promotes response selection. Moreover, irrespective of the representational content of the stimuli, interference was greatest when distractors disappeared 200 ms before target onset, compared to a 50 ms interval. This pattern suggests that conflict strength may decrease linearly as the temporal delay between flanker and target presentations becomes shorter.

An important aspect to be addressed is how representational contents can influence the recruitment of cognitive resources and contribute to conflict resolution when body- and non-body related semantic categories are intermixed and activated within the same stimulus array. In Experiment 5, we devised a new Flanker task using hands and leaves as stimuli to induce cognitive interferences. We aimed to investigate whether incongruencies between these representations impact behavior hypothesizing a direct replication of the facilitatory effect induced by hand stimuli in information processing.

Experiment 5

Differential cognitive interference induced by hand and leaf stimuli.

Experiment 5 confirmed that cognitive interferences were sensitive to stimulus content. Specifically, distracting leaf flankers interfered to a greater extent with hand target processing than hand flankers did with leaf target, suggesting a higher engagement of attentional resources required for conflict resolution. Indeed, while for the RTs the difference between indices was not significant ($t(23) = 1.212$; $p = 0.238$) the congruency effect for the accuracy was lower when hands flanked the leaf (5.94 ± 1.03) rather than when the leaves flanked the hand target (9.43 ± 1.04; $t(23) = 4.203$; $p = 0.0003$). In a similar vein, the index of the RTs/Acc ratio confirmed that leaves caused a higher degree of interference in the performance (15.79 ± 1.24) respect to hands (12.82 ±1.13; $t(23) = 3.204$; $p = 0.0039$; Fig. 6).

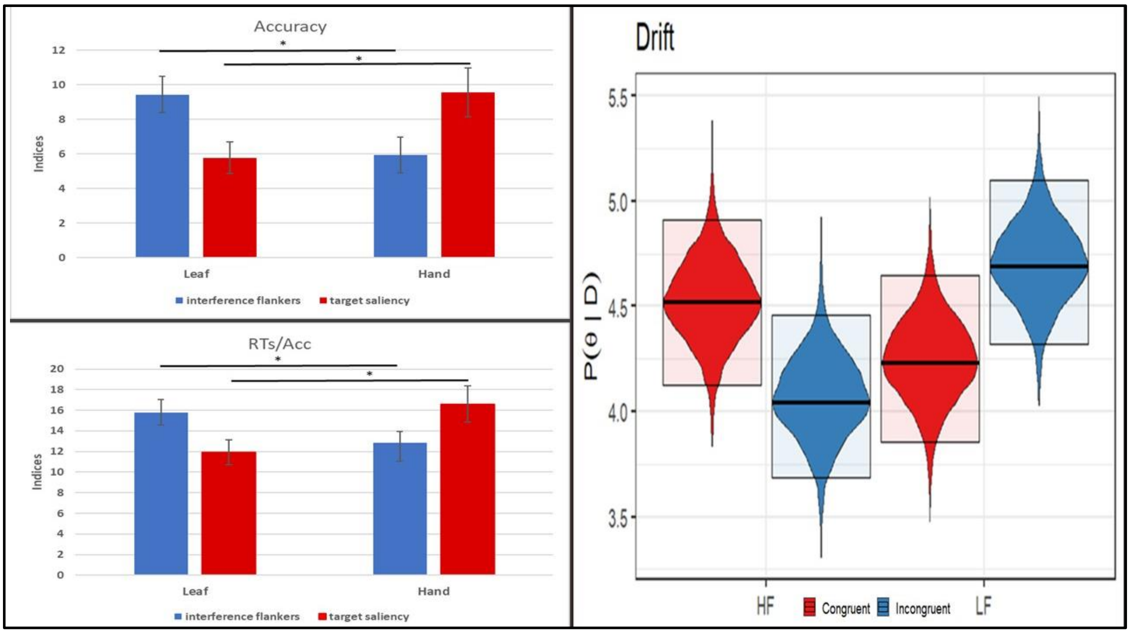


Figure 6. Bar plots representing the interference indices (in blue) and target saliency indices (in red) for accuracy (ACC) and overall performance (RT/Acc) in Experiment 5. A single asterisk (*) denotes comparisons where $p < 0.05$; double asterisks (**) denote comparisons where $p < 0.001$. Violin plots represent the posterior distribution of drift parameters in the BDDM, box outlines represent the 95% HDI and the darker central horizontal line represents the mode of the posterior distribution. The ≠ symbol indicates differences between conditions.

This effect appears to be linked to different rates of evidence accumulation, as shown by the BDDM analysis, which indicated that the accumulation rate favored congruent trials for hand stimuli and incongruent trials for leaf stimuli. This may reinforce the idea that body-related representations facilitate performance monitoring. Further support for this interpretation comes from the index reflecting overall behavioral performance (i.e., the RTs/Accuracy ratio; see the Supplementary), which was significantly impaired in the incongruent hand condition, specifically when hands were flanked by leaves. These findings suggest that body-related representations not only support performance monitoring but also exert a positive influence on behavior. Notably, a similar facilitatory effect has been reported in a recent study in which women with restrictive anorexia nervosa and matched neurotypical controls performed two versions of the Flanker task, using either body silhouettes or letters [18]. While patients showed overall poorer performance in both tasks reflecting impairment in processing body representations, neurotypical participants exhibited greater efficiency in resolving body-related rather than letter-based conflicts. This points to a potential advantage of body contents in reducing cognitive interference during conflict resolution. However, based on the analyses on interferences, we could not determine whether this pattern reflects (i) reduced distracting power of hand flankers, or (ii) the absence of a facilitation advantage for hand targets. To refine this interpretation by disentangling flanker-related interference from target-related facilitation we complemented the analyses by adding two additional indices, target-saliency leaf index and target-saliency hand index, which isolate the contribution of the target while holding flanker content constant across content types. No differences emerged for RTs (t(23) = 1.158; p = .258). For accuracy, a significant effect was observed (t(23) = 2.621; p = .0153), indicating greater target saliency for hands (9.57 ± 1.42) than for leaves (5.79 ± 0.91). The RT/accuracy index showed a similar pattern (t(23) = 2.245; p = .0346), again revealing stronger target-related facilitation for hands (16.60 ± 1.75) relative to leaves (11.93 ± 1.20). Overall, these supplementary analyses suggest that the asymmetric interference observed in Experiment 5 may reflect both reduced distracting effects of hand flankers and enhanced facilitation associated with hand targets, further clarifying the role of corporeal content in this type of experimental manipulation.

Discussion

Making choices between two or more alternatives may activate representational conflicts that need to be rapidly solved for selecting the best possible option. The performance monitoring system is crucial for detecting conflicts and minimizing errors [4, 5]. In the present study, we used five variants of the Flanker task [8] to elicit motor-perceptual conflicts and investigate how content-specific representational incongruencies could modulate the flanker congruency effect in independent participant samples. Importantly, despite differences in the stimulus categories, we employed a standardized interference index that corrected each stimulus class for its own baseline performance (i.e., the incongruent condition relative to the congruent condition within the same semantic category). This approach allowed us to control potential confounding effects driven by low-level perceptual features. Overall, our findings indicate that the interference index reflecting the flanker congruency effect was smaller in the Hand-Flanker (HF) task than in the Letter-Flanker (LF) task. Although we designed different task-related internal structures and purposes, the facilitation was consistently replicated, indicating a possible computational gain in processing cognitive interferences driven by hand stimuli. The results are further corroborated by a Bayesian analytical approach based on the drift-diffusion model confirming in many cases the advantage of body-related representation in orienting the accumulation of information.

Our results expand on previous studies based on variants of the Flanker tasks with conflicting body-related stimuli. For example, stimuli consisting of faces expressing negative, positive, or neutral emotions have been presented to investigate affect-driven representational interference arising during conflict processing and attentional orientation [39, 18, 40]. Despite the impairment of overall performance for faces showing negative compared to those showing positive emotions, flanker faces with a negative valence induced less interference, suggesting a possible dissociation between cognitive interference and behavioral outcomes [39, 18].

In addition to body parts, images of whole bodies have also been used as target/flanker stimuli in studies exploring the extent to which incongruent postural, emotional, and weight-related representations elicit congruency effects [15, 17, 18]. In particular, Oldrati and colleagues [17] investigated attentional allocation in the resolution of conflicts generated by representations of faces and bodies that were (in)congruent in terms of affect and gender. Their results indicate that emotion-related conflict alters the processing of central targets to a greater extent than gender-related representations. Moreover, the stronger interference associated to body vs face representations suggests that sub-categorial representations of corporeal stimuli may play a selective and differential role in modulating attentional control and conflict resolution [17].

A crucial question, therefore, is whether the cognitive gain associated with body-related stimuli may promote conflict resolution and can be exploited by the monitoring system to optimize performance. A closer examination of our behavioral patterns indicates that a lower interference elicited a better overall performance in the case of conflicting hands than in the case of conflicting letters in Experiments 1, 2, and 5. In Experiment 3, the facilitation driven by hand stimuli did not lead to improved behavioral outcomes, except in the domain of motor inhibition, where we observed a lower rate of false alarms for the hands compared to the letters. However, no clear effects were observed in Experiment 4 regarding this link. One may speculate that body-related versus non-body-related stimuli are particularly relevant for the performance monitoring system in conditions of conflict, reducing the computational complexity of information processing that underlies cognitive interference. In this regard, neuroscientific studies have shown that body and body parts highlight the presence of dedicated content-specific processing for corporeal information [41, 42]. For example, neurophysiological investigations using paradigms different from those employed in the present study have shown that seeing and embodying a virtual avatar from a first-person perspective while performing an erroneous reach-to-grasp movement elicits an evoked potential that is a typical signature of error detection (the observational error-related negativity [31]) regardless its frequency of occurrence [32], and parametrically related to the magnitude of the erroneous movement [33]. Moreover, EEG evidence indicates that the encoding of corporeal stimuli is associated with an electrocortical code reflecting a power increment of theta oscillations and arising from the activation of the extrastriate body area [43]. Interestingly, the injection of exogenous alternating current in the theta rhythm over the midfrontal–occipital network can facilitate the processing of cognitive conflicts driven by hand stimuli and improve response times [44].

Furthermore, across the experiments, performance is in some cases better for incongruent hands than for incongruent letters (e.g., Experiment 1 and 2 across all variables; Experiment 4 for RTs), whereas in other cases the difference is non-significant (e.g., accuracy and RT/accuracy in Experiments 3 and 4). In Experiment 5, although incongruent trials cannot be directly compared within the same content domain because hands and leaves were intermixed, we observed that the incongruent hand condition (target hand / leaf flankers) elicited poorer accuracy and overall worse performance than the incongruent leaf condition (target leaf / hand flankers). In this case, leaf flankers produced greater interference than hand flankers, even though no significant differences emerged between the congruent conditions. This indicates that the interference indices in Experiment 5 do not depend on facilitation in processing congruent stimuli (as was likely the case for letters in the other experiments).

Aan important issue that deserves discussion, therefore, concerns the clarification of the possible mechanisms contributing to reducing interference during the processing of conflicting hands with respect to letter stimuli. On the one hand, a role may have been played by their dissimilarity in visual complexity [45], which influenced information processing in such a way as to make the congruent condition more difficult in HF than in LF tasks. Indeed, while letters are configurations characterized by simple lines arranged in basic structures, realistic images of human hands may require more perceptual resources and impose complex information processing, thereby eliciting slower responses and a larger proportion of errors. Such an interpretation may explain why in our experiments congruent hands were mostly associated with poorer performance than congruent letters (e.g., slower RTs and lower accuracy). Hence, the smaller difference between congruent and incongruent trials in the HF tasks was likely due to the structural complexity of hand representations, which required more processing effort. This, in turn, may have influenced how congruent stimuli were encoded, resulting in a weaker flanker congruency effect.

On the other hand, an alternative explanation calls into play the possible link between perceptual and attentional resources activated during conflict processing. These studies (see for example: [46, 47]) have shown that high levels of cognitive load, such as the incongruent conditions, may capture perceptual resources and orient attention accordingly, thereby affecting the interference effect of task-irrelevant information on target processing. In this sense, the reduced compatibility effects we found in the HF conditions may have been due to facilitation in resolving incongruent conflicts driven by the higher perceptual load associated with processing hands compared to the lower perceptual load associated with processing letters. However, neither perspective seems to receive full support. In Experiments 1 and 2, indeed, the hand incongruent rather than the letter incongruent conditions induced a better performance. If visual complexity played a role in the identification of hand stimuli compared to letters, we would expect that incongruencies in hand representations would also lead to greater impairment in performance compared to letters. In Experiments 3 and 4, despite the interference indices being higher for LF than for HF, no difference was observed between the incongruent conditions. This may have been partly due to the internal organization of the tasks, which included no-go trials and thus affected not only the interaction between attention and perception but also the dynamics between conflict processing and response inhibition. In Experiment 5, however, the hand target flanked by leaves was more difficult to process than the leaf target flanked by hands. Since the congruent conditions did not result in significant differences between each other, it appears that perceptual load did not primarily modulate the interference by reducing the distance with the incongruent conditions. Instead, it is possible that hand flankers required less perceptual and cognitive resources, thereby impairing the distracting effect on the leaf target, and ultimately reducing the interference. Finally, the BDDM models suggest that most of the effects observed in these experiments are linked to the drift parameter, which represents the velocity of evidence accumulation.

Also, the reduced cognitive interferences elicited by hand stimuli may reflect several, not necessarily mutually exclusive, factors that could account for the facilitation observed in our experiments. Body-related stimuli may be inherently more salient and meaningful to humans, engaging perceptual, motor, and cognitive resources in a way that enhances behavioural performance compared to other object categories or semantic representations. Empirically, previous studies have reported attentional biases toward faces and body parts [48, 49], as well as faster visuospatial processing for bodies and faces relative to noncorporeal objects (e.g., chairs; [50]). Consistent with previous experimental investigations, therefore, our results suggest that even in the domain of cognitive interference, body-related representations may entail preferential discrimination and stimulus categorization that selectively activate information processing and reduce congruency effects. Moreover, the manual response modality adopted in our tasks may also have contributed to modulating response strategies, due to its correspondence with the stimulus effectors (i.e., the hands). With regard to this, studies seem to confirm such a link. It has been shown, for example, that during a perceptual suppression task requiring judgments of stimuli superimposed over hand representations, participants reported a facilitation effect in the visual suppression when their right-hand position was congruent with the orientation of the hand stimuli [51]. Similarly, Ionta et al. [52] found that when participants evaluated the orientation of right-hand pictures, they showed slower reaction times when their real right hand was occluded from vision compared to when it was visible. These findings suggest that visual and motor representations of the hand are tightly integrated and can interact to enhance perceptual processing when stimulus–effector congruency is present. In line with this view, it is possible that in our tasks, the use of manual keypress responses maintained the activation of hand representations during ongoing information processing, potentially improving cognitive interference induced by hand-related stimuli This interpretation is also consistent with evidence showing that congruency effects can vary as a function of response modality [53-55]. However, none of the experiments in our study included manipulations specifically designed to determine whether the observed effects could be explained by effector–stimulus content compatibility. This issue should be addressed in future investigations._Our empirical study indicates that body-related information may enhance performance monitoring during conflict processing. This further suggests that representational systems activated by specific semantic content may affect response selection in conditions of motor competition and the ability to resolve cognitive interference to achieve task goals and optimal performance. A possible experimental implication of the study could involve measuring cognitive interference associated with different bodies and body parts to explore whether these effects reveal functional sub-domain aspects of information processing in conditions of conflicts. Finally, some limitations of the study should be acknowledged. Previous research has shown that response inhibition and control, particularly involving frontal and frontolateral neural structures, may be influenced by demographic variables such as gender, age, education, and socioeconomic status [56-58], as well as by individual traits such as impulsivity [59]. In our experiments, we collected information on age, gender, and education (see the Supplementary File for the analyses attempting to explore the effects of these covariates on the interference indices), but not on socioeconomic status or impulsivity. Therefore, we cannot determine the extent to which these factors may have contributed to the observed congruency effects in our manipulations. It is important to note, however, that in each experiment, individual variability was the same across the Flanker tasks using either hand or letter stimuli. Both the tasks shared the same structure and logic and differed only in the type of conflict-inducing stimulus. This consistent pattern points to a potential functional advantage of the performance monitoring system when processing hand-related stimuli under conditions of stimulus–response competition. Further systematic studies are needed to specifically address the eventual influence of individual differences.

Methods

Transparency and Openness

We report how we determined our sample size (see the Power Analysis section), all exclusions from the data sets (see the Data Processing section for each experiment), all manipulations, and all measures collected as part of the study. All data, analysis code, and research materials are available at https://osf.io/q5chj/. Data were analyzed using Statistica 12 (StatSoft. Inc. Tulsa, USA), R version 4.0.0 and the ggplot package, version 3.2.1.

Power Analysis

An a priori power analysis was conducted using MorePower 6.0.4 [60] to estimate an adequate sample size. Since in the current study, we had administered behavioral tasks similar to those employed in our previous work on the role of band-specific modulation in content-driven conflicts, we re-analyzed the data set from Fusco et al., [44] to calculate and compare the cognitive interference induced by conflicting hands and letters in the sham condition. The effect size corresponding to the significant difference between these tasks, t(30) = 2.054; p = 0.048; d = 1.21, was used in the power analysis. The analysis indicated that a sample of at least 24 usable participants was required to achieve statistical power (1 − β) of .80 with an alpha (α) threshold of .05.

Five independent samples were, therefore, recruited in five different Experiments. All the 131 participants were healthy Caucasian young adults (overall mean age: 25.25 ± 3.77 years) who were mostly undergraduate or graduate students. Given the relative homogeneity of these samples, it is possible that other samples representative of different populations, such as older adults, or a sub-clinical or clinical population, may perform differently in these tasks, reflecting a potential constraint on the generalizability of the findings.

Low-Level Stimulus Features

Across all experiments, stimuli were compared based on low-level perceptual features. Specifically, for each stimulus (congruent and incongruent; hands, leaves, and letters), we measured luminance, contrast and chromatic properties using a customized R script, available for download and inspection at the following link: https://osf.io/q5chj/files/fuyjw. Luminance was quantified as the mean pixel intensity of each image converted to grayscale, providing an estimate of overall brightness. Contrast was computed as the standard deviation of grayscale pixel intensities, reflecting the variability of luminance values within each image. Chromatic characteristics were assessed by calculating the mean values of the red, green, and blue channels, obtained by averaging the intensity of each colour component across all pixels. All averaged data points for these dependent variables were analysed according to the factorial models used in each experiment. No significant differences emerged between stimulus categories for any of the features considered. Full details on the data analysis and the scores for the low-level perceptual features are available in the OSF project folder titled “Low-Level Features of the Stimuli”.

Experiment 1

Participants

Twenty-eight Caucasian volunteers were enrolled in the study (14 female; mean age: 25.2 ± 3.3 years; mean years of education: 15.82 ± 3.06; all right-handed). All participants had normal or corrected-to-normal vision, reported no color blindness or achromatopsia and no history of brain damage or neurological or psychiatric diseases, and were naïve to the purpose of the experiment. All participants gave their written informed consent to take part in the study. The research protocol was approved by the ethics committee of the Santa Lucia Foundation in accordance with the 2013 Declaration of Helsinki (protocol reference: CE/PROG.766).

Task and Stimuli

Two adapted versions of the Eriksen Flanker task, one presenting letters (the Letter-Flanker task; LF) and the other presenting hands (the Hand-Flanker task; HF) were administered. In each condition, five equidistant, horizontally adjacent stimuli were briefly presented in the center of the screen: these consisted of a central target stimulus and lateral flankers (two on each side). Participants were exposed to two types of target/flanker combinations: in the congruent condition, the target and the flankers were identical and thus activated a single motor response; in the incongruent condition, the target was different from the flankers and thus induced a different stimulus-response association. Participants were asked to respond only to the central target, by pressing one of two available keys, and ignore the lateral flankers. The interference effect, therefore, reflected the difference in performance outcomes (i.e., the ability to respond quickly and accurately) between the congruent and the incongruent conditions; a smaller interference effect (i.e., faster reaction times and greater accuracy) was expected in the former compared to the latter. For the LF task, the stimuli were the capital letters H and S; and for the HF task they were hands, with either the palm or the back displayed (see Fig. 6). All stimuli were presented in either pink or brown; the color was irrelevant to the task goals in Experiment1, but this differentiation was used to create additional experimental conditions in Experiments 3 and 4 (see below).

Each trial began with the presentation of a fixation cross at the center of the screen for 200 ms. Immediately after its disappearance, the cross was replaced by the flankers, which were presented for 100 ms before the target was added to the screen, with the entire stimulus (target and flankers) presented for a further 50 ms. Starting from the offset of the stimulus, a window of 800 ms was allowed for the participant's response. No feedback was provided on the participant's performance, except on trials in which no response was provided, after which the message "*Non hai risposto!*" ("You did not answer!") was presented for 500 ms, and after slower responses (with a latency of more than 500 ms), when a 1000 Hz beep was delivered through headphones (Fig. 7). Participants were required to provide their response on each trial as quickly and accurately as possible by pressing one of two keys on a keyboard, following the instruction: "press the key on the left only when the target is H / the hand back and the key on the right when the target is S / the hand palm"; the allocation of keys to stimuli was counterbalanced across participants. The task-irrelevant variable of color was not mentioned in the instructions.

All trials were administered to each participant in a random order. Target and flankers had the same width and height (subtending a visual angle of 9.31° horizontally and 2.32° vertically) for both hands and letters and were presented on a gray background on a 47 × 30 cm computer monitor. The central point of each stimulus in each string was distant from the central point of the neighboring one 3 cm (2.14°). The tasks were developed using the E-prime 2.0 professional software package (Psychology Software Tools Inc., Sharping, PA, USA).

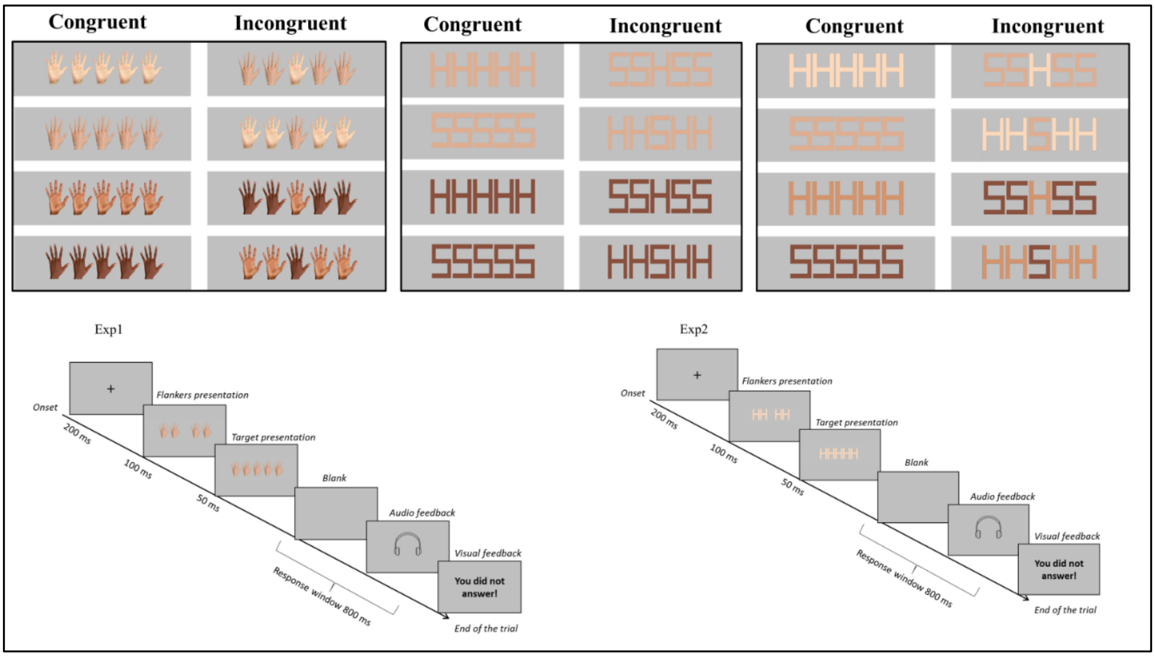


Figure 7. Task and stimuli. Hand and letter stimuli and conditions in the Hand- and Letter-Flanker tasks (top panel: Experiment1, left and central group of stimuli; Experiment2, left and right group of stimuli). The bottom panel shows the timeline of a representative trial in Experiment 1 and 2.

Procedure

Each participant was invited to participate in two experimental sessions, one for each task (LF and HF) on the same day. For each session, they were asked to sit at a comfortable distance of 80 cm from the PC monitor, in a dimly lit and soundproof room. Each session began with the presentation of the task instructions and a training phase in which the participants could familiarize themselves with the task. During the training phase, 16 trials were administered (8 congruent, 8 incongruent) in two consecutive blocks. Subsequently, in the experimental phase, 320 trials were presented for the relevant task in each session over two separate blocks (each consisting of 160 trials, of which 80 were congruent trials and 80 incongruent), with an inter-block interval of 5 minutes. Each block lasted approximately 3–4 minutes, depending on the individual participant’s response speed. The order of tasks was counterbalanced across participants, and each participant took a 15-minute break between the two sessions.

Data Processing

The flanker congruency effect, or interference index, was computed for each dependent variable (DV), i.e., reaction times (RTs) to correct responses (ms), accuracy (Acc; % correct responses), and the ratio between these two variables (RT/Acc). The ratio of average RTs and accuracy (RT/Acc) provides a measure of the quality of participants' performance during cognitive tasks and reflects the overall cost of the information processing required to resolve representational conflicts [17, 61, 18, 62]. The interference index was computed using the following formula:

$$\text{interference index} = [(DV_{IC} - DV_{CC}) / (DV_{IC} + DV_{CC})] \times 100,$$

where IC and CC denote values of the DV in the incongruent and congruent conditions, respectively [19]. For the DV of Acc, the formula was modified such that the IC value was subtracted from the CC value to avoid negative values. Thus, for all DVs, a higher value for the index indicated a larger interference effect.

Each dependent variable was analyzed using repeated-measures ANOVA, following a 2 (Task: HF vs. LF) × 2 (Color: brown vs. pink) factorial design testing the contribution of both perceptual and semantic features in the processing of conflicting representations. Post hoc tests were conducted using Tukey correction for multiple comparisons. In the case of variables for which a Kolmogorov–Smirnov test for normality failed to confirm a Gaussian distribution, the data were standardized via log-transformation (log10) and normality was checked again. In cases where normality violation persisted, nonparametric Friedman ANOVA and Wilcoxon matched pairs tests (with Bonferroni correction for multiple comparisons) were performed. RTs < 150 ms were removed from the analyses (2.6% of the trials). The performance of four participants was rather poor (more than 2.5 standard deviations outside the sample means for the accuracy) and they were not included in any analysis. Thus, data from *n* = 24 participants were entered into the final analysis. RTs, Acc and RTs/Acc were analyzed following a 2 (Task: HF vs. LF) × 2 (Color: brown vs. pink) × 2 (Congruence: congruent vs. incongruent) factorial design. For completeness, the individual analyses of RTs and

Acc are described in the supplementary materials. Here we report the behavioral index (i.e., RTs/Acc ratio) reflecting the overall performance.

A complementary analysis was also conducted in which a Bayesian drift-diffusion model (BDDM) was used to capture conflict-related aspects of the time-constrained binary decisions made during task performance [38]. It is important to note that previous studies using the DDM in the Flanker task, even if required the participants to be as fast and accurate as possible, adopted liberal response windows (see for example [63]) so that responses could be provided without temporal constraints. In the tasks administered in all the experiments of the present study we designed a limited response window of 800ms to increase task difficulty. Since the RTs collected during task performance were, on average, lower than 550 ms (see the Supplementary), we were able to fit the data using the BDDM and evaluate decisional strategies. In particular, all checks show that the Bayesian models adequately represent the data, suggesting that in this case, the BDDM is adequate for the study (see the posterior predictive checks in the Supplementary). Moreover, we assumed that both drift and boundary separation might be modulated by the independent factors of Congruence (CC vs. IC), Task (LF vs. HF), and stimulus Color (brown vs. pink); only the intercept was estimated for the parameters relating to bias and non-decision time, as these effects were expected to be constant across all levels of each of the independent factors. Random effects were included in the model in the form of an intercept for each participant. BDDM models were fitted in R 4.0.0 (R core Team, 2020) using the brms package, version 2.12.0 [64, 65], with two independent Hamiltonian Markov Chains (each with 2000 iterations) comprising 1000 burn-in iterations, which were excluded from the analysis [66]. The results are reported in terms of the 95% Highest Density Interval (95% HDI; [67]). To test whether the 95% HDI in each test represented evidence supporting the alternative or the null hypotheses, this value was compared to a region of practical equivalence (ROPE) of −0.5 to 0.5 [68]. A 95% HDI lying entirely outside the ROPE was taken as sufficient evidence to accept the alternative hypothesis; a 95% HDI lying entirely within the ROPE was taken as sufficient evidence to accept the null hypothesis; and a 95% HDI lying partially inside and partially outside the ROPE was considered to represent an inconclusive result. In the main text, we describe only those results suggesting acceptance of the alternative or the null hypothesis; complete tables of all results are provided in the Supplementary materials. When necessary, post hoc tests were conducted to compute the 95% HDI of differences.

Bayesian diagnostic indices, such as the posterior predictive checks in terms of posterior predictive p-values [66], the Gelman–Rubin diagnostic index [69], and the number of effective iterations [66], indicated that all the models fitted as part of these analyses were reliable (more details are provided in the Supplementary).

Experiment 2

Participants

Twenty-five Caucasian volunteers took part in Experiment 2 (15 females; mean age: 22.96 ± 4.03 years). None had participated in Experiment 1. All participants had normal or corrected-to-normal vision, reported no color blindness or achromatopsia and no history of brain damage or neurological or psychiatric diseases, and were naïve to the purpose of the experiment.

Task, Stimuli and Procedure

Task, stimuli, and procedure were identical to those used in Experiment 1. However, the color of hands and letters, which were consistently pink and brown, were adjusted to provide a similar perceptual difference between flankers and target combined in the same stimulus array (see Fig.6). Specifically, we extrapolated from the central area of hand stimuli four colors and optimized letters accordingly: pink palm/H (RGB: red =256; green = 217; blue = 186) and back/S (RGB: red =223; green = 174; blue = 149) brown palm/H (RGB: red =212; green = 148; blue = 186) and back/S (RGB: red =137; green = 81; blue = 62).

Experiment 3

Participants

Twenty-five Caucasian volunteers took part in Experiment 3 (12 female; mean age: 25.7 ± 3.1 years; mean years of education: 15.54 ± 2.34; 2 left-handed). None had participated in Experiment 1 and Experiment 2. All participants had normal or corrected-to-normal vision, reported no color blindness or achromatopsia and no history of brain damage or neurological or psychiatric diseases, and were naïve to the purpose of the experiment.

Task and Stimuli

The task and stimuli were identical to those used in Experiment 1 in most respects. However, to incorporate the Go/NoGo component of the task, we added a set of conditions (see Fig. 8) and modified the rules to restrict participants' responses to trials in which certain features of the stimuli were present. Specifically, participants were required to withhold their motor response to stimuli in which the central target was the back of a hand, or a letter S depicted in brown, or the palm of a hand or the letter H depicted in pink (no-go trials); hence, the color of the stimulus was explicitly task-relevant in this experiment. The instructions provided to participants were as follows: "press the key on the left only when the back of the hand / the letter S are pink and, the key on the right when the palm of the hand / the letter H are brown". Response keys were counterbalanced across participants. On no-go trials in which the participant failed to withhold their response, a visual feedback message "*Falso allarme!*" ("False alarm!") was displayed on the screen for 500 ms. On go trials (i.e., when the target was the back of a hand or letter S depicted in pink, or the palm of a hand or letter H depicted in brown). As in the previous experiments, participants were required to provide a response as quickly and accurately as possible.

Stimuli were displayed as in Experiment 1 and the same feedback were provided in the case of missing and slow responses. All go and no-go trials in each t ask were presented in a random order.

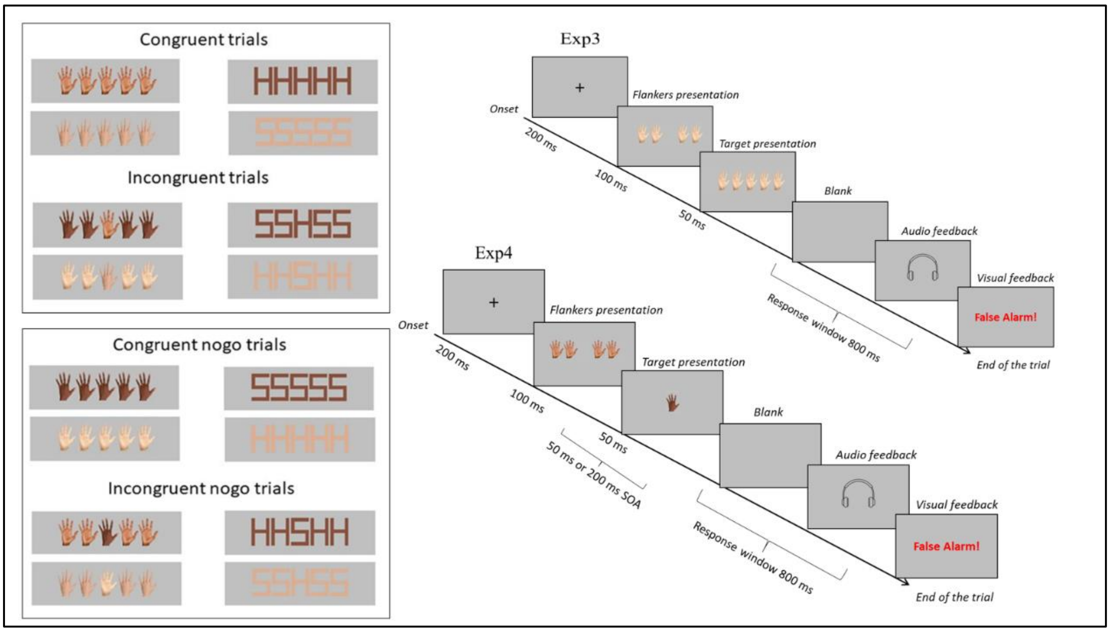


Figure 8. Task and stimuli. Hand and letter stimuli and conditions in the Hand- and Letter-Flanker tasks of Experiments 3 and 4. The right part of the panel shows the timeline of a representative nogo trial.

Procedure

Most aspects of the procedure were identical to Experiment 1 and Experiment 2. The 16 trials presented in the training phase consisted of 12 go trials (six congruent, six incongruent) and four no-go trials (two congruent, two incongruent) over two consecutive blocks, and an additional third training block was provided if required. In the experimental phase, 320 trials were presented for the relevant task in each session over two separate blocks, each consisting of 160 trials, of which 120 were go trials (60 congruent, 60 incongruent) and 40 were no-go trials (20 congruent, 20 incongruent), with an inter-block interval of 5 minutes.

Data Processing and Analysis

Variables and behavioral indices were computed and analyzed using ANOVAs with the same repeated-measures factorial design. However, for Experiment 3 we conducted an additional 2 (Task: HF vs. LF) × 2 (Color: brown vs. pink) × 2 (Congruence: congruent vs. incongruent) ANOVA over the proportion of false alarms (FAs) to test differences between the conditions also on response inhibition.

Data from one participant were excluded from all analyses due to a technical failure (data overwriting); thus, data from $n = 24$ participants were entered into the final analyses. Only data from go trials were entered into the BDDM analyses.

Additionally, we computed an inhibition index *d*' for use as a covariate to specifically test whether skill in inhibiting a response on no-go trials is a good predictor of performance in Flanker-like tasks. The inhibition index *d*' was computed as follows [70]:

$$d' = z(\text{Correct Rejections}) - z(\text{False Alarms}).$$

Details of this analysis are provided in the supplementary materials.

Experiment 4

Participants

Twenty-six Caucasian volunteers were recruited to participate (11 female; mean age: 25.8 ± 3.1 years; mean years of education: 14.83 ± 3.26; 5 left-handed). None had taken part in either Experiment 1, Experiment 2 or Experiment 3. All participants had normal or corrected-to-normal vision, reported no color blindness or achromatopsia and no history of brain damage or neurological or psychiatric diseases, and were naïve to the purpose of the experiment.

Task and Procedure

The task, response instructions, and procedures were identical to those of Experiment 3, with a single main difference, namely the addition of a delay variable. Specifically, flankers (displayed for 100 ms) disappeared before either 50 ms or 200 ms prior to presentation of the target (which was displayed for 50 ms ; see Fig. 8).

Data Processing and Analysis

In Experiment 4, for the interference indices, the repeated-measures ANOVA followed a 2 (Delay: 50 vs. 200 ms) × 2 (Task: HF vs. LF) × 2 (Color: brown vs. pink) factorial design. Data from one participant were excluded from all analyses due to a technical failure (data were not recorded); data from a second participant were excluded due to poor performance (more than 2.5 standard deviations outside the sample mean in the accuracy). Thus, data from $n = 24$ participants were entered into the final analyses. RTs, Acc (See the Supplementary) and RTs/Acc followed a 2 (Delay: 200 vs 50) x 2 (Task: HF vs. LF) × 2 (Color: brown vs. pink) × 2 (Congruence: congruent vs. incongruent) factorial design. Data of False Alarms (FA) were non-normally distributed in two conditions, so a non-parametric analysis was conducted accordingly. Only data from go trials were entered into the BDDM analyses, and the d’ from the Go/No-Go component of the task was used as predictor.

Experiment 5

Participants

Twenty-six Caucasian volunteers participated in this study (13 females; mean age: 26.5 ± 4.51; mean years of education: 16.41 ± 1.97; 1 left-handed). None of them took part in any of the previous four experiments. All participants had normal or corrected-to-normal vision, reported no color blindness or achromatopsia and no history of brain damage or neurological or psychiatric diseases, and were naïve to the purpose of the experiment.

Task and Stimuli

In this version of the Flanker task, we reintroduced the classical structure in which perceptual-motor conflicts emerge during information processing, activating only two motor response representations that compete to achieve task goals. However, we used two different categorial stimuli, namely hand and leaf, which were combined to design the congruent (i.e., target/flanker: hand/hand or leaf/leaf) and incongruent (i.e., target/flanker: hand/leaf or leaf/hand) conditions. The five horizontal elements composing the stimulus array were equidistant subtending a visual angle of 3.58°

between the central points of adjacent elements, with the same width and height (visual angle of 4.29° horizontally and 2.51° vertically) and were screened at the center of a white background of a 47 × 30 cm PC monitor. Stimuli were presented randomly in a grey color (Fig. 9) and were matched for low-level features (e.g., luminance, contrast). Each trial began with a fixation cross lasting 200ms, followed by flankers' onset that primed the target for 100ms. The target and flankers were then presented in a single array for a further 50ms. Participants had a temporal window of 800ms to provide their response by pressing one of two corresponding keys, namely the yellow key (the 'q' button of the keyboard) when the target was the leaf, or the blue key (the 'p' button of the keyboard) when the target was the hand (the keys were counterbalanced across the participants). If responses were finalized after 500ms, a beep sound (1000Hz) was triggered through headphones to signal the need to be faster. If no response was provided, the visual feedback "You did not answer!" ("*Non hai risposto!*") appeared in order to reorient the attention of participants over the task goal.

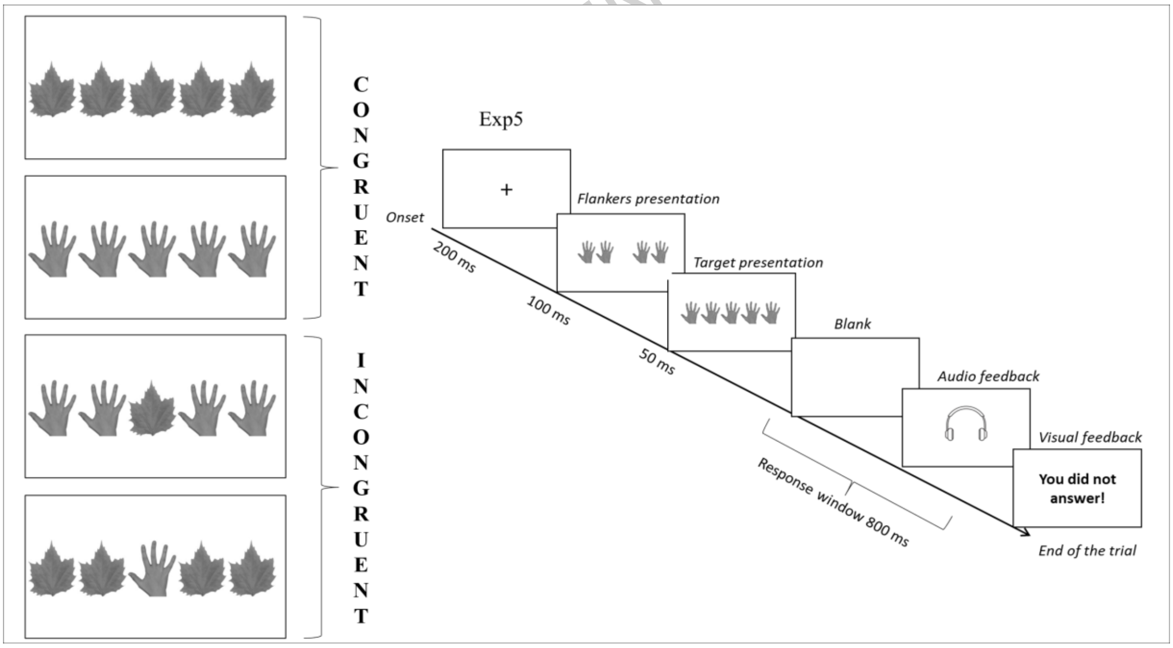


Figure 9: Stimuli and timeline of a trial of the hand-leaves Flanker task of the Experiment5

Procedure

Participants were to sit comfortably 80cm distant from the PC monitor. Two training blocks were administered to familiarize with the task rules (20 trials, 5 congruent hand, 5 congruent leaf, 5 incongruent hand, 5 incongruent leaf), and if needed, a further third training block was provided. Following this phase, participants were required to perform four consecutive experimental blocks each consisting of 160 trials (80 congruent: 40 hand/ 40 leaf; 80 incongruent: 40 hands, 40 leaf) and respond as fast and accurately as possible to stimuli. A 5-minute break was granted between each block.

Data Processing

A 2 (Congruence: congruent, incongruent) x 2 (Stimuli: hand, leaf) repeated measure ANOVA(s) were computed for the RTs, Acc and RTs/Acc dependent variables. Congruency indices were calculated following the formula reported in Experiment1 but considering hand and leaf stimuli separately into two different indices:

$$\text{interference index leaf} = [(DV_{ICl} - DV_{CCl}) / (DV_{ICl} + DV_{CCl})] \times 100$$

where ICl refers to the incongruent (target leaf/ flankers hand) and CCl to the congruent conditions (target leaf/flankers leaf) for the leaf stimulus. Instead, for the hand representation we computed:

$$\text{interference index hand} = [(DV_{ICh} - DV_{CCh}) / (DV_{ICh} + DV_{CCh})] \times 100$$

where ICh refers to the incongruent (target hand/flankers leaf) and CCl to the congruent conditions (target hand/flankers hand). To separately quantify (i) the net cost induced by flankers of different content and (ii) the facilitation associated with targets of different content we also computed two further indices for all variables:

$$\text{target saliency leaf index} = [(DVICl - DVCCh) / (DVICl + DVCCh)] \times 100$$

where ICl refers to the incongruent (target leaf/ flankers hand) and CCh of the incongruent leaf stimulus to the congruent conditions (target hand/flankers hand) of the hand stimulus. Instead, for the hand representation we calculated:

$$\text{target saliency hand index} = [(DVICh - DVCCl) / (DVICh + DVCCl)] \times 100$$

where ICh refers to the incongruent (target hand/flankers leaf) and CCl to the congruent condition (target leaf/flankers leaf) of the leaf stimulus. Comparisons were analyzed by means of repeated measures t-tests for dependent samples. Data from two participants were excluded from all analyses due to missing data in one block; thus, data from n = 24 participants were entered into the final analyses.

Declarations

Author contributions statements

Gabriele Fusco: Conceptualization, Methodology, Formal analysis, Software, Investigation, Writing - Original Draft, Writing - Review & Editing.

Michele Scandola: Conceptualization, Software, Formal analysis, Writing - Review & Editing.

Marco Spitaleri: Investigation.

Salvatore Maria Aglioti: Conceptualization, Funding, Supervision, Resources, Writing - Review & Editing

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Conflicts of Interest

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial or non-financial interest in the subject matter or materials discussed in this manuscript.

Ethics approval

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of the Santa Lucia Foundation in accordance with the 2013 Declaration of Helsinki (protocol reference: CE/PROG.766).

Consent to Participate

Informed consent was obtained from all individual participants included in the study.

Availability of data and materials

The datasets generated and analyzed during the current study are available in the open science framework (OSF) repository, https://osf.io/q5chj/ and will be stored at the Department of Psychology, Sapienza University of Rome, Italy. None of the experiments were preregistered.

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