ORIGINAL ARTICLE

The impact of stimulus format on task inhibition during task switching

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Abstract

Switching between competing tasks is supported by active inhibition of the preceding task. The level of task stimulus processing at which interference between competing tasks must occur for inhibition to be recruited is still unclear. Here, we investigated whether inhibition is recruited by task conflict occurring at an early or late (semantic) stage of task stimulus processing by dissociating the task stimulus format from its meaning. In two experiments, participants performed three different numerical judgment tasks on numerical stimuli that could be presented as digits or number words (e.g., "6" or "six") in a cued task-switching procedure. The effects of the change of stimulus format for the inhibition of the previous task were investigated and assessed by the N-2 task repetition cost, an index of the extent to which task representations are inhibited. The N-2 task repetition cost observed in the same stimulus format condition disappeared when target stimuli on task N-1 were presented in a different format from stimuli of task N-2 and N. This occurred both when the format changed from digits to number words stimuli (Experiment 1) as well as when it changed from number words to digits stimuli (Experiment 2). Results indicated that task set inhibition is recruited very early during the stimulus processing stage. They also provided evidence that task inhibition is not tied to task preparation processes but operates as a reactive, rather than proactive mechanism of conflict resolution.

Introduction

The ability to counteract interference from automatic processing of currently irrelevant information is crucial for efficient adaptation to an ever-changing environment. In our daily-life activities, what information is relevant and what is irrelevant at any given moment changes continuously and rapidly according to changes of internal goals or external circumstances. Frequently, it happens that previously irrelevant information becomes suddenly relevant for a new goal (and vice versa). Imagine having a phone conversation with a friend during your daily walk and suddenly a passer-by stops you asking for driving directions. Your friend keeps talking on the phone, and somehow you try to ignore what he is saying to concentrate on what the passer-by is asking for. Information that was relevant a moment ago becomes now irrelevant, although it continues to interfere with the processing of new information. At some point, you would need to suppress interference from the automatic processing of information from the (previously relevant) phone

conversation to concentrate on the new (and now relevant) conversation. Maybe you might also need to switch back to your friend's conversation for telling him to wait a moment, and then switch again to the passer-by's conversation. The ability to rapidly instantiate, adjust, and modify this processing balance between promoting the processing of relevant information while suppressing irrelevant one in accordance to changes of internal goals or external circumstances is crucial for intentional behavior.

Inhibitory mechanisms are thought to support the optimization of this balance at many different levels of information processing (e.g., Aron, 2007). Inhibition can target the processing of specific perceptual features (e.g., the red color; Tipper, 2001) or information coming from specific portions of the visual field when they interfere with current goals. Inhibition can also target the representation of a specific action (Logan, 1994). Crucially, not just single perceptual and motor representations (e.g., stimuli and responses) can be inhibited, but inhibition can also target high-level mental representations, such as the representation of the whole set of potentially relevant stimuli, responses, and stimulus–response association rules that are transiently bound together for the execution of a specific task (such as "press the brake pedal if the traffic light shows the red light

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and keep going if it shows the green light"; Arbuthnott & Frank, 2000; Mayr & Keele, 2000). The cognitive representation of the whole set of stimuli, responses, and rules that guides behavior for the achievement of a specific goal in a specific moment can be defined as a task set (Kiesel et al., 2010; Monsell, 2003; Sakai, 2008).

The inhibition of no longer appropriate task sets is crucial when a rapid switching of tasks is required (see Koch et al., 2010 for a review). Task set inhibition is assumed to reduce the interference from the just executed task in order to support the efficient instantiation of a new task set (Allport et al., 1994; Goschke, 2000; Hübner et al., 2003), so that when switching from task A to task B, the task set A is suppressed to prevent it from interfering proactively with the execution of the B task. However, this "backward" inhibition (Mayr & Keele, 2000) can also result counterproductive when it is required to switch back to a task that has been executed and then switched away from very recently (as in an A–B–A sequence of tasks) as this task could be still subject to previous inhibition. In this situation, switching back to this task would also require overcoming (residual) inhibition, requiring extra time for task performance. This extra-time is referred to as the N-2 task repetition cost (Arbuthnott & Frank, 2000; Mayr & Keele, 2000), and it is measured as the performance difference between switching back to a recently executed task (as in an A–B–A task sequence) and switching back to the same task when it has been executed less recently and it should not suffer (or suffer less) from previous inhibition (as in a C–B–A task sequence). The N-2 task repetition cost is considered a marker of task inhibition (but see also Grange et al., 2017).

Backward inhibition is assumed to come into play during task switching, especially in conditions of high interference between the previous and current task (Koch et al., 2010). Task conflict can occur both at the level of task stimuli and task responses. The first one is related to the sharing of stimuli between tasks (overlapping stimulus sets), and it comes into play when different tasks are required on the same category of stimuli because each stimulus can afford potentially both the current and the alternative task (bivalent stimuli). An example of this type of conflict is when a parity (odd/even) and a magnitude (smaller/larger-than) judgment tasks must be sequentially performed on number stimuli. The second source of conflict is related to the sharing of responses between tasks (overlapping response sets), and it comes into play when the same motor responses are involved for responding to different tasks so that each response has a different meaning in different tasks (bivalent responses; Gade & Koch, 2007). An example of this type of conflict is when the same left and right button-press responses are used for responding to both parity (odd/even) and magnitude (smaller/larger-than) judgment tasks so that each response corresponds to two different dimensions, one for each task

(e.g., left button: odd and small numbers; right button even and large numbers). While previous evidence indicates that task inhibition is recruited for conflict resolution at both stimului (Arbuthnott & Woodward, 2002; Sdoia & Ferlazzo, 2008) and response (Gade & Koch, 2007; Schuch & Koch, 2003) processing level, where exactly, in terms of specific processing stages, this conflict must occur for inhibition to be triggered is still debated. In the present study, we focused on the conflict at the level of task stimuli representations and investigated the boundary conditions of overlapping stimulus sets under which task inhibition occurs. Specifically, task interference at the level of stimulus representation may occur at an early stage of processing (e.g., perceptual), for instance because stimuli of competing tasks share basic perceptual dimensions, or it can occur at a late stage of processing, such as at the semantic level, because stimuli of competing tasks refer to the same semantic category (e.g., numbers). We investigated whether task inhibition during task switching is triggered by interference between task stimuli occurring at an early (dimension) or late (semantic) stage of stimulus representation. To this aim, we explored the impact of stimulus format on the inhibition of competing task sets in a cued task-switching procedure and assessed whether inhibition of the previous task set is recruited despite a change of the stimulus format from the previous to the current task. The role of stimulus format on task inhibition has never been investigated, though it is informative regarding the underlying nature of the task set inhibition as it can inform about the processing level at which task inhibition does operate.

In two Experiments, we dissociated the stimulus format from the stimulus meaning by using digits and number words as task stimuli (e.g., "seven" and "7") on three numerical judgment tasks presented in a cued task-switching procedure. We investigated the effect of a change in the stimulus format on the inhibition of the previous task as assessed by the N-2 task repetition cost. The sequence of tasks was manipulated to assess the basic N-2 task repetition cost (ABA vs. CBA), and we also manipulated the stimulus format on the trial N-1 (i.e., digits or number words), which could be the same or not as the stimulus format on the trials N-2 and N. This resulted in a 2 (ABA and CBA) X 2 (same vs different stimulus format on N-1) experimental design (ABA and CBA vs AB'A and CB'A, with the prime indicating a different format of the target stimulus). If inhibition is recruited during task switching because of the interference occurring at the semantic level of the competing stimulus representations, then the inhibition of the previous task set should be triggered regardless of the stimulus format (e.g., symbolic or verbal) in which stimuli of the two competing task sets are presented, because nothing changes at the semantic level of processing. In such a case, the transition from A to B (AB) should trigger the same amount of inhibition as the transition from A to B' (AB'), producing the N-2

task repetition cost when switching back to the inhibited task regardless of the code of the triggering stimulus (B and B'). Under this hypothesis, no differences are expected between ABA and AB'A performance. On the contrary, if inhibition is recruited because of the interference occurring at an early stage of processing, at the level of perceptual dimensions of stimuli (e.g., stimulus format), then a reduced amount of interference should occur in the condition of non-overlapping stimulus format, namely when the stimulus format changes from one task to the next in the context of a task switching, and a reduced amount of inhibition should be recruited, resulting in a smaller N-2 task repetition cost. Under this hypothesis, faster performance is expected on AB'A than ABA task sequence. To note that regardless of whether the format of the target stimulus was a digit ("3") or a number word ("three"), the stimulus itself remained bivalent (or trivalent in this case) as it can afford each of the three possible tasks equally. This means that the stimulus sets remained semantically overlapping even if the stimulus format changed.

Experiment 1

Methods

Participants

Thirty students (females = 14, mean age = 22.93, SD = 3.2) were recruited at the Faculty of Psychology of Sapienza University of Rome to participate in the study. The sample size was determined by power analysis to detect a medium-to-large partial eta squared of 0.3 for the interaction with a power of 0.9 to increase the chance of replicability. This partial eta squared was chosen considering the effects size of the 2 by 2 sequence by condition interaction in previous studies involving manipulation of the trial N-1 (e.g., Scheil & Kleinsorge, 2014).

All participants had a normal or correct-to-normal vision. They all were naïve to the aims of the study and provided written informed consent. The study was approved by the Institutional Review Board of the Department of Psychology of Sapienza University.

Procedure

On every single trial of a cued task-switching procedure, participants performed one of three possible judgment tasks on a numerical stimulus (from 1 to 9, excluding 5) presented centrally on a computer monitor: a magnitude task, indicating whether the stimulus was smaller or larger than five; a parity task, indicating whether the stimulus was an odd or an even number; and a position task, indicating whether

the stimulus was centrally or peripherally positioned along the number line (3, 4, 6, and 7 were central digits; 1, 2, 8, and 9 were peripheral ones). A task cue appeared at the center of the screen 600 ms before each stimulus was presented, indicating the task to perform. Task cues consisted of black geometrical shapes, a square, a diamond, and a circle, cueing the parity task, the magnitude task, and the position task, respectively. Stimuli could be presented as digits or as their relative Italian words (e.g., "3" or "TRE"). Participants responded with their left or right index finger by pressing the keys "A" and "L", respectively, over a standard QWERTY keyboard according to the current cue-task rule. The response set was completely overlapping, so that participants responded with the "A" key-press to smaller-than-5, even, and centrally positioned numbers, and with the "L" key-press to larger-than-5, odd, and peripherally positioned numbers.

The cues and the stimuli were black and centrally presented over a grey background. Cues were about 6 by 6 cm. Stimuli were about 2 (height) by 1 cm (width) for digits, whereas words ranged from a width of about 3 cm for the shortest number words (e.g., "SEI") to a maximum of about 9 cm for the longest number word ("QUATTRO"). The task was programmed in E-Prime 2.0 and was ran on a 17-inches computer monitor (refresh rate: 60 Hz) placed approximately 60 cm from the participant. Instructions about the task were verbally provided and displayed on the screen to each participant before the experiment.

The task consisted of three blocks of 190 trials each. A trial started with the presentation of a task-cue. Participants were required to respond as fast and accurately as possible. If participants made an error or took longer to respond (> 2500 ms), auditory error feedback was provided for an additional 50 ms. After the participant's response, the stimulus disappeared, and the next cue was presented with 200 ms of blank interval.

The task sequence was pseudo-randomly determined for each participant with the constraints of having approximately 65 trials for each of the four conditions of interest (ABA, CBA, AB'A, and CB'A). Also, the stimulus could never be repeated on two consecutive trials. For each participant, 190 task triplets were randomly selected from all the combinations of task rules (parity, position, magnitude) and conditions of interest (ABA, CBA, AB'A, and CB'A) and then concatenated together in a unique task sequence made up of 570 single trials. Each trial was categorized on the basis of the type of task switches on the preceding two trials and only triplets of interests (ABA, CBA, AB'A, and CB'A) were considered for the main analyses. In each individual sequence, the mean number of observations for each of the four types of triplets of interest was 68 (SD = 10).

Stimuli consisted of digits on 75% of trials and number words on the remaining 25% of trials. This proportion

is constrained by the necessity to have the same number of observations for the four conditions of interest (ABA, CBA, AB'A, and CB'A) with the minimum number of trials. Indeed, within the four triplets of interest, only two trials out of twelve are different format trials (16%). We increased this proportion to 25% after having ran simulations in which the proportion of different format trial was manipulated to obtain the maximum number of balanced observations for the four conditions of interest with the minimum number of trials. The task sequence also resulted in repetition trials (approximately 65 trials) that we decided to keep in the task sequence despite the N-2 repetition cost is reduced when task repetitions are allowed (Philipp & Koch, 2006; Scheil & Kleinsorge, 2019). We reasoned that repetition trials allow to reduce potential expectancy-related effects due to having only switch trials.

Participants performed 72 practice trials. The practice trials consisted of 30 digit trials (10 for each task, non-inter-mixed), 30 mixed digits/words trials (75% / 25%) (10 for each task, non-intermixed), and 12 trials (4 for each task) wholly intermixed. If necessary, participants repeated the practice phase for a maximum of one additional time. The experiment consisted of three blocks of 190 trials each.

Design

Mean individual reaction times (RTs) and error rates (ERs) were analyzed in a 2×2 repeated measures analyses of variance (ANOVAs) with task sequence (ABA and CBA) and stimulus format on trial N-1 (i.e., digit vs. number word) as independent variables.

Results

Each single trial was classified in accordance with the task and the stimulus format of the two preceding trials (N-2 and N-1) and only ABA, CBA, AB'A, and CB'A trials were included in the analyses.

The first two trials of each block and sequences in which an error occurred on trials N-1 or N-2 were removed from all analyses, while for analyses of RT data, errors in trial N were removed as well. Trials with RTs longer than 2500 ms or shorter than 200 ms were also removed from the RTs analyses. Individual performances with a number of correct observations per cell lower than 2 standard deviations from the mean number of correct trials per cell in at least one cell of the design were also excluded (two participants). Since previous research suggested that episodic retrieval may contribute to N-2 repetition cost (Gade et al., 2017; Grange et al., 2017) trials in which the stimulus was identical as that in N-2 were excluded from the analysis. The mean number of trials per cell included in the RTs analysis was 42 in ABA, 42 in CBA, 34 in AB'A, and 37 in CB'A. The proportion of

type I errors among all rejected null hypotheses was controlled by setting the false discovery rate (FDR) to 0.05. The FDR was estimated through the procedure described in Storey and Tibshirani (2003). The bootstrap procedure was used to estimate the $\pi 0$ parameter (Storey et al., 2004). In our results, the 0.05 level of significance corresponded to an FDR < 0.05.

Mean RTs are depicted in Fig. 1. The sequence × format ANOVA on RTs revealed non-significant main effects of sequence ($F(1, 27) = 3.27$, $p = 0.082$, $\eta^2_p = 0.108$, $\eta^2_G = 0.008$) or stimulus format ($F(1, 27) = 0.16$, $p = 0.694$, $\eta^2_p = 0.006$, $\eta^2_G = 0.0002$) but a significant sequence by stimulus format interaction ($F(1, 27) = 10.99$, $p < 0.005$, $\eta^2_p = 0.289$, $\eta^2_G = 0.010$). Paired t test revealed significantly slower RTs on ABA than CBA sequences when the stimulus format did not change on trial N-1 ($t(27) = 3.54$, $p < 0.005$, $d_z = 0.668$) showing an N-2 task repetition cost. Most important for the purpose of the present study, AB'A RTs did not differ from the CB'A RTs ($t(27) = -1.16$, $p = 0.871$, $d_z = -0.030$). Crucial to ascertain that the decrease of N-2 repetition cost was indeed due to a reduction in RTs in AB'A, rather than an increase in CB'A, we found that RTs on AB'A were significantly faster than those on ABA ($t(27) = 3.07$, $p < 0.005$, $d_z = 0.580$). No significant difference did appear between RTs on CB'A and CBA condition ($t(27) = -1.66$, $p = 0.109$, $d_z = -0.313$).

Accuracy was analyzed in a sequence × format ANOVA on the squared-root arcsine transformed proportion of errors. Results did not reveal any significant main effect or interaction (sequence: $F(1, 27) = 0.09$, $p = 0.763$, $\eta^2_p = 0.003$, $\eta^2_G = 0.0001$; format: $F(1, 27) = 0.38$, $p = 0.543$, $\eta^2_p = 0.014$, $\eta^2_G = 0.0003$; sequence × format: $F(1, 27) = 0.07$, $p = 0.789$, $\eta^2_p = 0.003$, $\eta^2_G = 0.00005$; mean accuracy percentage: ABA = 65.2; AB'A = 65.8; CBA = 65.3; CB'A = 66.2).
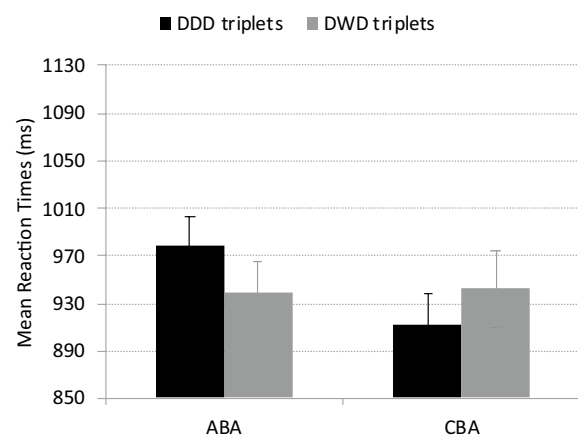
Fig. 1 Mean reaction times on alternating (ABA) and non-alternating (CBA) task sequence for the same (DDD) vs different (DWD) stimulus format condition on trial N−1. *D* digit, *W* word stimulus. Bars denote standard errors according to Morey (2008)

We also directly tested whether the N-2 task repetition costs observed in the two format conditions (same or different) were significantly different from zero. Results revealed that the N-2 task repetition cost was significantly different from zero (Fig. 2) when the stimulus format did not change on trial N-1 ($t(27) = 3.54$, $p < 0.005$, $d_z = 0.668$) while it did not differ from zero when the format changed on trial N-1 ($t (27) = -0.16$, $p = 0.871$, $d_z = -0.030$). Together, these results indicate that after a change of stimulus format, participants are faster in switching back to a task that has been switched away from very recently (AB'A) than when stimulus format remained the same (ABA).

Discussion

Results of Experiment 1 showed that the N-2 task repetition cost disappeared in the change format condition compared to the same format (control) condition. This indicates that in the context of a change of stimulus format from the task N-2 to the task N-1 the inhibition of the previous task is not recruited and, in the absence of this inhibition, switching back to the abandoned task (AB'A) results easier than when the stimulus format on trial N-1 remained the same (ABA). Since the semantic representation of the target stimulus does not depend on the format in which the stimulus is presented ("4" or "four"), the elimination of the N-2 task repetition cost due to the stimulus format change indicates that task inhibition is not recruited at the semantic level of stimulus processing. Otherwise, one would have found the same inhibitory effect on both the same and change format conditions. On the contrary, the elimination of the N-2 task repetition cost due to the stimulus format change (even maintaining the semantic overlapping) indicates that task inhibition is tied to interference at a lower level of stimulus

Fig. 2 Mean N-2 task repetition cost for the same (DDD) vs different (DWD) stimulus format condition on trial N-1. *D* digit, *W* word stimulus

representation (e.g., perceptual), interference that occurs on condition of dimensional overlapping (e.g., same format) rather than semantic overlapping, and that is hence reduced in the condition of a format change. This indicates that inhibition is recruited at an early rather than a late stage (i.e., semantic) of stimulus processing, a stage where the perceptual properties of the stimulus are also included.

One may wonder whether the imbalance in the frequency of word and digit trials could have affected results. For example, it can be assumed that the relatively few encounters with the deviating stimulus format (i.e., number word trials) lead to stronger attention towards this stimulus and, as a consequence, to stronger task set activation of the respective task. This, in turn, may reduce the need for inhibition of the task in N-2 because the activation level in N-1 overweighs the conflict due to persisting activation of trial N-2 (we are grateful to an anonymous reviewer for suggesting this possibility). We tested this hypothesis by comparing performance on the frequent (digit) and infrequent (word) stimulus format trials on the ground that stronger attention toward the infrequent stimulus format would determine a better performance on this type of trial compared to the frequent format trials. We observed the opposite pattern of results, with significantly slower RTs on the infrequent format than on the frequent format trials ($t(27) = -8.78$, $p < 0.001$, $d_z = -1.66$). This seems to rule out the hypothesis that inhibition is reduced because of a stronger task set activation on the infrequent format trials due to stronger attention.

Hence, results from Experiment 1 indicate that task inhibition during cued task switching does not depend on the semantic interference between competing task stimuli representations, rather it is recruited at a lower level of the stimulus representation. The generalizability of such a conclusion was further investigated in Experiment 2 by reversing the proportion of number words and digits stimuli.

Experiment 2

To further investigate the elimination of the N-2 task repetition cost under the change format condition and the generalizability of results from Experiment 1, the proportion of words and digits trials was reversed in Experiment 2, so that in the 75% of the trials the stimuli consisted of number words and in the remaining 25% consisted of digits. Hence, in Experiment 2, the N-1 different format condition is a word-digit-word triplet of tasks while the N-1 same format condition is a word-word-word triplet of tasks. As for Experiment 1, the hypothesis that inhibition is recruited by semantic interference between bivalent stimuli predicts no differences in the N-2 task repetition cost between the same and different format condition (ABA = AB'A). On the
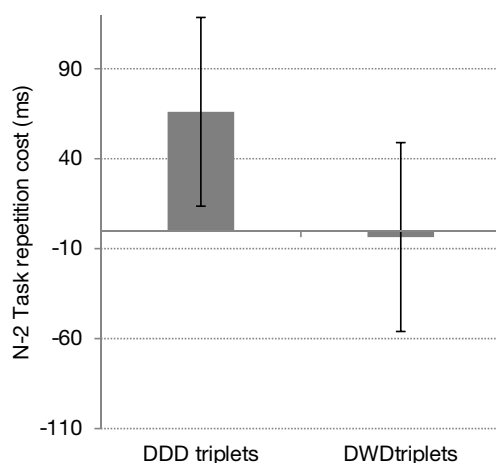
contrary, the hypothesis that inhibition is recruited by early interference between competing stimuli (e.g., when format overlaps) predicts a reduced N-2 task repetition cost when interference is reduced by the change of stimulus format.

Methods

Participants

Thirty students (females = 19, mean age = 22.42, SD = 3.24) were recruited at the Faculty of Psychology of Sapienza University of Rome to participate in the study. All participants had a normal or correct-to-normal vision. They all were naïve to the aims of the study and provided written informed consent.

Procedure

The task and the procedure were identical to the Experiment 1, with the only difference consisting in the proportion of trials with number words and digits stimuli which now included words number stimuli on 75% of the trials and digits stimuli on the remaining 25% of trials. Thus, the N-1 different format condition is a word-digit-word triplet of tasks while the N-1 same format condition is a word-word-word triplet of tasks.

Results

The same experimental design and statistical analyses of Experiment 1 were conducted on Experiment 2. The same criteria of the Experiment 1 were used for data trimming, resulting in five participants being excluded from the analysis. The mean number of trials per cell included in the RTs analysis was 36 in ABA, 38 in CBA, 30 in AB'A, and 32 in CB'A.

Mean RTs of all conditions are depicted in Fig. 3. The pattern of results was very similar to the one observed in Experiment 1. The 2 (sequence) × 2 (format) ANOVA on mean RTs revealed non-significant main effects of the sequence ($F(1, 24) = 1.30$, $p = 0.266$, $\eta^2_p = 0.051$, $\eta^2_G = 0.003$) or stimulus format ($F(1, 24) = 1.45$, $p = 0.240$, $\eta^2_p = 0.057$, $\eta^2_G = 0.003$) but a significant sequence by stimulus format interaction ($F(1, 24) = 4.88$, $p < 0.05$, $\eta^2_p = 0.169$, $\eta^2_G = 0.008$). Paired t test showed significantly slower RTs on ABA than CBA sequences on the same format trials ($t(24) = 2.20$, $p < 0.05$, $d_z = 0.440$), revealing an N-2 task repetition cost. Crucially, AB'A RTs did not differ from the CB'A RTs ($t(24) = -0.60$, $p = 0.552$, $d_z = -0.120$). Important, RTs on AB'A were significantly faster than those on ABA ($t(24) = 2.355$, $p < 0.05$, $d_z = 0.471$). CB'A RTs did not differ significantly from those on CBA condition ($t(24) = -0.78$, $p = 0441$, $d_z = -0.156$).
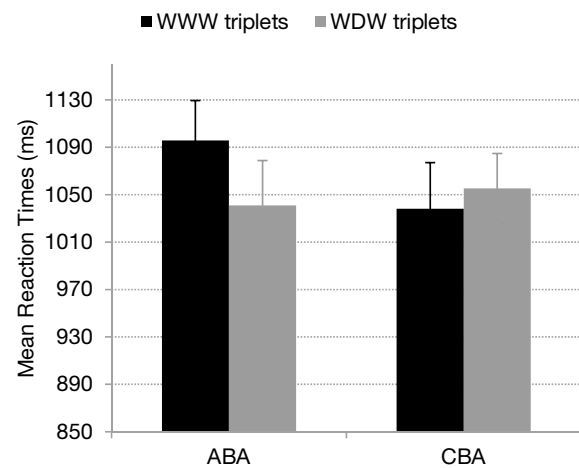
Fig. 3 Mean reaction times on alternating (ABA) and non-alternating (CBA) task sequence for the same (WWW) vs different (WDW) stimulus format condition on trial N-1. *D* digit, *W* word stimulus. Bars denote standard errors according to Morey (2008)
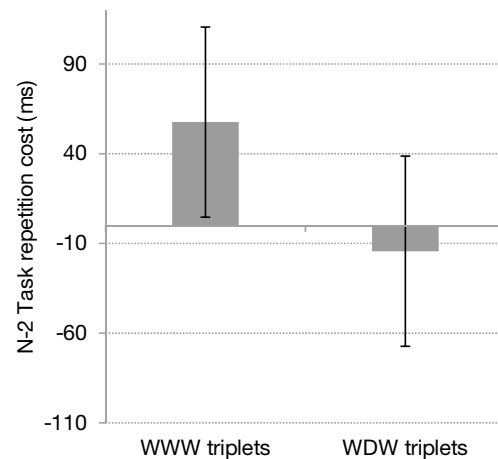
Fig. 4 Mean N-2 task repetition cost for the same (WWW) vs different (WDW) stimulus format condition on trial N-1. *D* digit, *W* word stimulus

Accuracy was analyzed in a sequence × format ANOVA on the squared-root arcsine transformed proportion of errors. Results did not reveal any significant main effect or interaction (sequence: $F(1, 24) = 0.007$, $p = 0.934$, $\eta^2_p = 0.0003$, $\eta^2_G < 0.0001$; format: $F(1, 24) = 0.001$, $p = 0.970$, $\eta^2_p = 0.00006$, $\eta^2_G < 0.0001$; sequence × format: $F(1, 24) = 0.23$, $p = 0.637$, $\eta^2_p = 0.009$, $\eta^2_G < 0.0001$; Mean accuracy percentage: ABA = 62; AB'A = 60; CBA = 62; CB'A = 62).

As in Experiment 1, we also tested whether the N-2 task repetition costs were significantly different from zero in the two format conditions (same or different). Results revealed that the N-2 task repetition cost was significantly different from zero (Fig. 4) when the stimulus format remained the same ($t(24) = 2.20$, $p < 0.05$, $d_z = 0.440$) while it did not

differ from zero when the format changed on trial N-1 (t (24) $=-0.60$, $p = 0.552$, $d_z = -0.120$).

These results resemble those from the Experiment 1 and showed that after a change of stimulus format participants are faster in switching back to a task that has been switched away from very recently (AB'A) than when stimulus format remained the same (ABA).

Discussion

Results of Experiment 2 were very similar to those from Experiment 1 in showing that the N-2 task repetition cost was eliminated when the stimulus format changes from one trial (N-2) to the next (N-1), indicating that in these circumstances the competitor task's inhibition is not recruited. Thus, reversing the proportion of digits and number words trials from the Experiment 1 did not change the observation that the N-2 task repetition cost was eliminated in the change format condition.

As for Experiment 1, we also tested whether the imbalance in the frequency of word and digit trials could have affected results on the ground that stronger attention toward the infrequent stimulus format would determine a better performance on this type of trials compared to the frequent format trials, without call for inhibition. We tested this hypothesis by comparing performance on the frequent (word) and infrequent (digit) stimulus format trials. Results revealed no difference between RTs on a frequent and infrequent format (t(24) $= 0.57$, $p = 0.58$, $d_z = 0.11$). This pattern of results seems to rule out the hypothesis that inhibition is reduced because of a stronger task set activation on the infrequent format trials due to stronger attention.

Hence, results from Experiment 2 indicate that task inhibition during cued task switching does not depend on the semantic interference between competing task stimuli representations, rather it is recruited at a lower level of the stimulus representation.

General discussion

The main issue addressed in the present study is related to the level of task stimulus processing at which interference between competing tasks must occur during task switching for inhibition of the previous task to be recruited. In two experiments we dissociated the stimulus format from the stimulus meaning by using digits and number words as task stimuli (e.g., "6" or "six") in a cued task-switching procedure, and investigated the effect of a change in the stimulus format for the inhibition of the previous task as assessed by the N-2 task repetition cost, an index of the extent to which task representations are inhibited. Dissociating the task stimulus format from its meaning allowed us to investigate whether inhibition is recruited by task conflict occurring at an early (perceptual) or late (semantic) stage of task stimulus processing. We found that the typical N-2 task repetition cost observed in the same format (control) condition disappeared when target stimuli on task N-1 were presented in a different format from stimuli of task N-2 and N. This occurred either when the format changed from digits to number words stimuli (Experiment 1) and when it changed from number words to digits stimuli (Experiment 2). These results demonstrate that task inhibition during cued task switching does not depend on interference at the semantic level of task stimuli representations, but it is recruited at a lower level of stimulus processing, for instance, at the level of object's properties representation (i.e., the stimulus format). Thus, the triggering mechanism of task inhibition is located at an early stage of stimulus processing.

The possibility must be considered that changes in performance due to the stimulus format transition could not be related necessarily to the transition from trial N-2 to N-1 (e.g., to the triggering of inhibition) but to the transition from N-1 to N (e.g., to the recovery from previous inhibition), as in both these transitions a change in the stimulus format does occur (we are grateful to Luca Moretti for suggesting this possibility). Specifically, let's assume that the same amount of inhibition is triggered from trial N-2 to N-1 regardless of a change in the stimulus format and that an enhanced recovery stage from this inhibition occurs from trial N-1 to N only when the stimulus format change from N-1 to N, so that only this latter process is responsible for the reduction of the N-2 repetition cost we observed in our data. Under this assumption, when comparing the AB'A and CB'A conditions, slower RTs are expected on the AB'A than CB'A. Indeed, in both these conditions a change in the format occurs from trial N-1 to N but on the AB'A trials the performance is further affected by the very recent execution of the A task, which should hence suffer from inhibition more than on the CB'A trials, as it happens for the typical N-2 repetition cost. However, this was not the case, as performance on AB'A did not differ from CB'A. Furthermore, the hypothesis that the observed effects are due to the format switch from trial N-1 to N (e.g., faster recovery from inhibition when the format changes) also predicts faster performance on CB'A than CBA, because the format switch only occurred on the CB'A and not on the CBA. Again, this was not the case, as in Experiment 1 the RTs were significantly slower on CB'A than CBA condition and in Experiment 2 CB'A RTs did not differ significantly from those on CBA condition. Hence, while the alternative explanation that the observed reduction of N-2 task repetition cost is due to the format switch from trial N-1 to N rather than to the switch from trial N-2 to N-1 can predict the faster RTs on AB'A than ABA, it is not consistent with the remaining pattern of results. However, all these are post hoc considerations, and

we think that future studies are still necessary to disentangle the effects of the format change on the triggering of inhibition from the recovery of inhibition.

Task inhibition is generally conceptualized (Koch et al., 2010) and computationally implemented (Sexton & Cooper, 2017) as a conflict resolution mechanism that is recruited when interference between tasks is detected at some point during task processing (Koch et al., 2010, 2018; Vandierendonck et al., 2010, for reviews). For instance, Houghton et al. (2009) argued that inhibition is attached flexibly to the part of the task set that causes the highest inter-trial conflict. Evidence exists that between-task conflict at the level of cue-target translation (Houghton et al., 2009), at the level of stimulus processing (Sdoia & Ferlazzo, 2008) and response processing (Gade & Koch, 2007; Schuch & Koch, 2003) all have a role in recruiting task inhibition. However, in conditions of high interference between tasks (e.g., overlapping of both stimulus and response sets) it is still unclear when and where exactly, in terms of specific processing stages, task inhibition takes place. At the response processing stage, for instance, it is undetermined whether the locus of task conflict resides at the selection (e.g., Schuch & Koch, 2003), preparation or execution stage of task responses (e.g., Philipp et al., 2007). At the stimulus processing stage, findings indicate the conflict at the level of stimulus-attribute selection as a possible functional trigger of task inhibition (e.g., Arbuthnott & Woodward, 2002; Hübner et al., 2003; Sdoia & Ferlazzo, 2008). For instance, in a previous study, we found that conflict at stimulus selection during intentional encoding of stimuli into short-term memory on trial N-1 can result in N-2 repetition costs (Sdoia & Ferlazzo, 2008). Present findings further delineate the specific component of task inhibition that is related to conflict at the stimulus processing stage, indicating that inhibition is recruited at the level of stimulus properties representation rather than at the semantic level of the stimulus representation.

Present results also need to be considered in view of the debate on the voluntary and automatic nature of task inhibition. A still open issue is whether backward inhibition operates as a proactive mechanism that can be carried out in an anticipatory manner during task preparation (e.g., before the target stimulus is actually presented; e.g., Prosser et al., 2020) or whether it operates as a reactive mechanism that is automatically triggered whenever interference between tasks is detected (e.g., Sexton & Cooper, 2017). In our procedure, participants did not know in advance the format of the target stimulus (e.g., during the cue-target interval), as the cue only provided information about the task to be performed. Furthermore, the tasks were the very same regardless of whether the stimulus was a digit or a word ("three" and "3"). Therefore, we can assume that advanced task preparation processes elicited by cue processing were the same on both types of format

conditions. Hence, the absence of the N-2 repetition cost on the different format condition allows the inference that task inhibition cannot be tied to task preparation processes carried out before the onset of the actual stimulus. Otherwise, one should have observed preparation-related inhibitory effects on the different format condition too. This observation is consistent with the hypothesis of task inhibition as a reactive rather than a proactive mechanism that comes into play whenever a conflict between tasks is detected (at the stimulus or response level). This is also consistent with the original observation of Mayr and Keele (2000) and other previous studies (e.g., Philipp & Koch, 2006) showing no preparation effect on N-2 repetition costs. However, since part of the task set reconfiguration process can only occur after the stimulus presentation (e.g., Rogers & Monsell, 1995), it cannot be excluded that task inhibition is tied to this exogenous part of task preparation. On the other hand, other studies reported task preparation effects on N-2 repetition costs (e.g., Gade & Koch, 2014; Philipp et al., 2007). For instance, a modulation of the N-2 repetition cost was found by manipulating the preparation intervals on trial N-1 and N-2, with the cost being more pronounced for long task preparation interval (Scheil & Kleinsorge, 2014). While further research is necessary to unambiguously define the contribution of task preparation processes to task inhibition, present findings are consistent with the view of task inhibition as a reactive mechanism.

Consistent with the idea that task inhibition is not tied to conceptual, high-level semantic representations of task stimuli but to specific low-level objects' properties representation, recent studies have found parietal regions of the brain, which are traditionally involved in conflict monitoring and detection of stimuli categories and properties (Corbetta & Shulman, 2002; Liston et al., 2006), to be specifically involved in task inhibition (Sdoia et al., 2020; Zhang et al., 2016).

The evidence that task inhibition does not operate on semantic representations of task stimuli may also suggest that the representations of the task components (e.g., stimuli) in working memory during task switching are not maintained in a verbal code. This would speak against the hypothesis of a verbal representation of task-set components in working memory (Baddeley et al., 2001; Emerson & Miyake, 2003; Goschke, 2000) and would be more consistent with the idea that task set components are represented in a non-declarative form, perhaps within a procedural component of working memory (Oberauer, 2009).

While further studies are still needed, present findings highlighted for the first time that task set inhibition does not operate on semantic representations of task stimuli, rather they indicate that task inhibition is recruited very early during the stimulus processing stage. They also

provide evidence that task inhibition is not tied to task preparation processes but operates as a reactive, rather than proactive mechanism of conflict resolution.

Declarations

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