Dissociable yet tied inhibitory processes: The structure of inhibitory control

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Abstract Cognitive and neural models have proposed the existence of a single inhibitory process that regulates behavior and depends on the right frontal operculum (rFO). The aim of this study was to make a contribution to the ongoing debate as to whether inhibition is a single process or is composed of multiple, independent processes. Here, within a single paradigm, we assessed the links between two inhibitory phenomena—namely, resistance to involuntary visual capture by abrupt onsets and resolving of spatial stimulus–response conflict. We did so by conducting three experiments, two involving healthy volunteers (Exps. 1 and 3), and one with the help of a well-documented patient, R.J., with selectively weakened inhibition following a lesion of the rFO. The results suggest that resistance to capture and stimulus–response conflict are independent, because (a) additive effects were found (Exps. 1 and 3), (b) capture did not correlate with compatibility effects (Exp. 1), (c) dual tasking affected the two phenomena differently (Exp. 3), and (d) a dissociation was found between the two in patient R.J. (Exp. 2). However, the results also show that these two phenomena may share some processing components, given that (a) both were affected in patient R.J., but to different degrees (Exp. 2), and (b) increasing the difficulty of dual tasking produced an increasingly negative correlation between capture and compatibility (Exp. 3), which suggests that when resources are withdrawn from the control of the former, they are used to control the latter.

Keywords Inhibition · Attentional capture · Stimulus–response compatibility · Dual task · Inferior frontal gyrus · Frontal operculum

The abilities to avoid being distracted by irrelevant items and to put a stop to undesired or incorrect actions are fundamental for everyday regulation of coherent and appropriate behavior. The question of whether multiple independent inhibitory processes or just one such process orchestrates behavior is the subject of ongoing debate. In a comprehensive review, Kok (1999) concluded that different kinds of inhibition might exist, with inhibition being organized in the form of a hierarchical network including different sections of the brain. His evidence stemmed from psychophysical, developmental, and electrophysiological studies conducted with the aid of a variety of paradigms. The diversity of inhibitory processes is a conclusion that has also been drawn in other reviews (Dagenbach & Carr, 1994; Dempster & Brainerd, 1995; Nee, Wager, & Jonides, 2007) and in empirical studies that have reported very low correlations among tasks supposed to involve inhibition (e.g., Casey et al., 2000; Fan, Flombaum, McCandliss, Thomas, & Posner, 2003; Kramer, Humphrey, Larish, & Logan, 1994; Shilling, Chetwynd, & Rabbit, 2002; Simon & Berbaum, 1990). The rather constant lack of such a correlation has been interpreted as evidence that different inhibition tasks call upon fundamentally different kinds of conflict resolution processes. It has also been suggested that, in such
cases, these processes should not relate to each other, because they apply independently to several information-processing streams (Fan et al., 2003). In a comprehensive meta-analysis of neuroimaging tasks, Nee et al. found that the activations in different inhibition tasks overlapped in a number of brain areas, but that there were also task-specific activations. The authors proposed that different inhibitory processes act on different stages of processing. However, the results of neuropsychological and brain-imaging studies have suggested that only one inhibitory process may regulate behavior (Aron, Fletcher, Bullmore, Sahakian, & Robbins, 2003; Konishi et al., 1999; Stelzel, Schumacher, Schubert, & D’Esposito, 2006), an idea also adopted by a number of neuroanatomical and cognitive models (Aron, 2007, 2011; Aron, Robbins, & Poldrack, 2004; Michael, Garcia, Fernandez, Sellal, & Boucart, 2006; Michael, Léte, & Ducrot, 2013; Watson & Humphreys, 1997). Here, the idea is that inhibition tasks across different modalities may involve a single cognitive process underlain by a single neural network (Chambers, Garavan, & Bellgrove, 2009; Chikazoe, Konishi, Asari, Jimura, & Miyashita, 2007; Hodgson et al., 2007; Konishi et al., 1999; Leung & Cai, 2007; Levy & Wagner, 2011; Peterson et al., 2002; Wager et al., 2005; Xue, Aron, & Poldrack, 2008). For instance, it has been suggested that this cognitive process might be related to monitoring for conflict (Botvinick, Braver, Barch, Carter, & Cohen, 2001) or the execution of operations that lead to inhibiting conflicting activities (Petersen & Posner, 2012).

One of the phenomena described by Kok (1999) is the inhibition of sensory events—for example, active resistance to involuntary visual capture by irrelevant items (de Fockert & Theeuwes, 2012). Visual stimuli appearing in the peripheral fields involuntarily capture attention, and yet the inhibition of sensory interference, meaning that capture can be reduced, has been shown to develop in various situations—namely, when participants have advance knowledge of the most probable location of the target (≥200 ms; Müller & Rabbit, 1989; Yantis & Jonides, 1990), when the target appears before a salient distractor (Michael, Jacquot, Millot, & Brand, 2005; Theeuwes, 1995), and when participants know precisely where a forthcoming target will be located (Michael, Kleitz, Sellal, Hirsch, & Marescaux, 2001). In some cases, residual capture may still be observed (Marzouki, Grainger, & Theeuwes, 2008; Michael, Boucart, Degreif, & Godefroy, 2001), and the extent of such capture is a sign of how strong active inhibition is (Michael et al., 2006). In other words, the weaker the residual capture effect, the stronger the inhibition. Another phenomenon of interest is motor inhibition—for example, resolving conflicting responses. When the location of a target does not correspond to the target feature relevant for the ongoing task, a spatial stimulus–response conflict (i.e., incompatibility) arises (Simon, Webster, & Craft, 1981), regardless of whether stimuli are placed in the horizontal or vertical plane (Hedge & Marsh, 1975). One interpretation of this effect is that the location of the stimulus, albeit irrelevant, is the dominant factor, and quickly influences action (de Jong, Liang, & Lauber, 1994). Thus, in conflicting situations, the involuntary tendency to respond to the target location rather than the relevant target feature has to be overridden (Frith & Done, 1986; Simon, 1969) for information from the display to be correctly translated into an appropriate motor action during response selection stages (Acosta & Simon, 1976; Kornblum, 1994). Interestingly, this phenomenon does not seem to change over time (Simon, Acosta, & Mewaldt, 1975). Active inhibition is thus required to resolve this kind of conflict: the weaker the residual compatibility effect, the stronger the inhibition.

The primary aim of the present study was to make a substantial contribution to the ongoing debate as to whether resistance to visual capture and the resolving of stimulus–response conflicts are due to the same inhibitory processes or to different ones (Aron, 2007; Kok, 1999; Kramer et al., 1994; Nee et al., 2007). We used a paradigm in which participants had to determine the location of the small gap presented on a precued target. On half of the trials, an item abruptly appeared so as to capture attention involuntarily and produce interference effects. So that spatial response compatibility could be assessed, the target’s location (i.e., the irrelevant feature) was either compatible or incompatible with the location of the gap (i.e., the relevant feature). To encourage participants to develop optimal inhibitory control, the location of the target was cued with a 100 %-valid central arrow cue, with a 200-ms interval between the appearance of the cue and that of the relevant feature. Combining the two paradigms in an orthogonal design meant that it was possible to investigate each of the effects (capture and compatibility) separately, as well as the potential interaction between them.

**Experiment 1**

**Method**

**Participants** A group of 33 (28 male, five female) healthy volunteers (mean age=28.6±3.1 years, mean education=11.9±2.2 years) took part in Experiment 1. Some were personal acquaintances of one of the authors, and others were recruited from among the staff of the Hôpitaux Civils of Strasbourg and Hôpital Roger Salengro of Lille (caregivers, cleaners, and secretaries), and of the Université Lyon 2 (cleaners and technical assistants). All reported normal or corrected-to-normal vision, were right-handers according to the Edinburgh inventory (Oldfield, 1971), and gave written consent for their participation.

**Stimuli and apparatus** The stimuli were gray squares (37.37 cd/m²) appearing inside a circle of equal luminance
and presented against a black background (0.034 cd/m²). At a viewing distance of 30 cm, the angular size of each square was 0.5°×0.5°, and the circle’s radius was 1°. Each square had a gap and was rotated 0°, 90°, 180°, or 270° clockwise. The target orientation was 0° or 180°, whereas that of the distractors was 90° or 270°. The stimuli were displayed in the middle of the screen of a Dell Latitude computer fitted with a Pentium II 200-MHz processor. The experiments took place in a dimly lit room.

Procedure At the start of each trial, a central fixation star was displayed for 500 ms, before being replaced with a small fixation point while the premask was added; the premask consisted of four circles, each with a small square in the center. The items were placed at the angles of an imaginary rectangle subtending an angular space of 3.8°×5.7°. The premask was displayed for 1,000 ms, following which an endogenous cue (a central arrow) was added for 100 ms, indicating the absolute location of the target. After a 100-ms interval, the stimulus display appeared in the form of a small gap on one side of each square. The target was the only item to have a gap on the upper or lower side. Participants were asked to locate the target’s gap (top or bottom) by hitting one of two predefined response buttons with the index and middle fingers of their right hand as quickly and accurately as possible. The display lasted until a response was given. Two capture conditions were tested: (a) In the distractor-present condition, a new, nontarget item was added abruptly to either the left or the right of fixation, but always on the same side as the target (to avoid undesirable lateral spatial-compatibility effects; see Fig. 1). (b) In the distractor-absent condition, no abrupt onset was presented. Two spatial stimulus–response compatibility conditions were also tested: (a) In the incompatible condition, the cued item was at the top of the display and the target’s gap was on the bottom side of the square, or vice versa; (b) in the compatible condition, the cued item was at the top of the display and the gap was on the top side of the square, or vice versa. Each participant completed a 16-trial training session, followed by an experimental session consisting of 192 trials (48 per condition). The four conditions were presented randomly and equiprobably. Response times (RTs) and errors were recorded by the computer. No breaks were proposed during the experiment, which lasted approximately 10 min.

Results and discussion

An analysis of variance (ANOVA) was carried out on the correct median RTs, with Capture Condition (distractor absent vs. present) and Compatibility Condition (compatible vs. incompatible) as within-participants factors. The main effects of capture condition $[F(1, 32)=33.4, p<.000002, \eta^2=.43]$; distractor absent (mean±1 SEM), 448±13 ms; distractor present, 461±13 ms] and spatial compatibility $[F(1, 32)=14.3, p<.0007, \eta^2=.57]$; compatible, 448±13 ms; incompatible, 462±13 ms] were significant, but the Capture×Compatibility interaction was not $[F(1, 32)=0.24, p>.62, \eta^2=.004]$; Fig. 2a]. Bayesian analyses (n=99, df effect=2) provided evidence that the interaction was, indeed, absent, as indicated by both the Bayes factor (81.6) and the high posterior probability that the absence of this interaction was correct $[P(H_0 | D)=.98]$; see Masson, 2011, for a comprehensive and accessible tutorial] That the main effects were present and interaction absent is a sign of additive effects (Sternberg, 1969), which suggests that these factors do not influence a common processing stage and, by extension, that resistance to visual capture may be achieved differently from how stimulus–response conflicts are resolved. An analysis of the correlation between the capture effect (distractor present minus absent) and compatibility effect (incompatible minus compatible) confirmed the absence of any link between them $[r(31)=-.05, p>.76]$; Fig. 2b]. This is consistent with previous findings that correlations in performance among different inhibition tasks are quite low (Fan et al., 2003; Kramer et al., 1994; Shilling et al., 2002; Simon & Berbaum, 1990). The results of Experiment 1, therefore, lend support to the view that multiple inhibitory processes exist. It is also interesting that the extents of the capture effect (distractor present minus absent) and the

\[ n = s(c - 1) \]—that is, the number of participants multiplied by the number of conditions minus one. The df effect is the number of free parameters in the model. According to the null hypothesis, there was no interaction effect, and thus the number of parameters was 0. The alternative hypothesis had two more parameters—that is, the difference between the compatible and incompatible conditions in the absence of a distractor could be different from the difference between the compatible and incompatible conditions in the presence of a distractor. Therefore, the number of parameters that distinguished the null and alternative hypotheses was two.
compatibility effect (incompatible minus compatible) were very similar (12 and 14 ms, respectively). The presence of such reliable, albeit shallow, effects is similar to the results of previous studies conducted using a variant of this paradigm (Michael & Buron, 2005; Michael et al., 2006).

The same analysis was carried out on the percentages of errors (Table 1). The main effect of capture condition did not reach significance \([F(1, 32)=0.56, p>.46, \eta^2=.02]\), but the effect of spatial compatibility was significant \([F(1, 32)=9.7, p<.004, \eta^2=.97];\) compatible, 1.0% ± 0.2%; incompatible, 3.2% ± 0.7%. The Capture × Compatibility interaction was not significant \([F(1, 32)=0.58, p>.45, \eta^2=.001]\).

**Experiment 2**

Previous neuropsychological and neuroimaging studies suggested that inhibition of irrelevant signals and prepotent responses depends on a mostly right-sided distributed neural network (Garavan, Ross, & Stein, 1999) involving the frontal lobes (Konishi, 2011; Stuss, Floden, Alexander, Levine, & Katz, 2001), particularly the inferior frontal gyrus (IFG; sometimes referred to as ventral premotor areas, or vPM) and its connections with subcortical structures (Aron et al., 2003; Aron et al., 2004; Chambers et al., 2009; Chikazoe et al., 2007; de Fockert & Theeuwes, 2012; Fan et al., 2003; Hodgson et al., 2007; Leung & Cai, 2007; Levy & Wagner, 2011; Picton et al., 2007; Xue et al., 2008). Several of these studies also suggested that these structures control all kinds of inhibition and constitute the neural substrate for a general inhibitory process (Stelzel et al., 2006). In two of our previous studies (Michael et al., 2006; Michael, Kleitz, et al., 2001), we presented the rare case of patient R.J., who has a specific lesion of the right frontal operculum (rFO), which is part of the IFG (Rizzolatti, Fogassi, & Gallese, 2002). His clinical profile revealed disturbed inhibitory processes. From several experimental investigations, it was apparent that he was unable to resist interference from abrupt onsets that were 100% task-irrelevant (i.e., increased attentional capture in comparison with control samples), whereas his abilities to orient attention, maintain task priorities, and code and maintain spatial locations were intact. Further investigations showed that he also had trouble inhibiting previously displayed visual items so that priority could be given to new ones. Accordingly, his failure in a variety of tasks involving inhibition is consistent with the idea that the right IFG might play a common inhibitory role across different tasks (Aron, 2007; Chambers et al., 2009; Leung & Cai, 2007; Levy & Wagner, 2011; Stelzel et al., 2006). However, the fact that R.J.’s inhibitory deficits could not be directly compared meant that it was not possible to draw any conclusions as to whether or not a single underlying process had been damaged (Caramazza, 1986; Caramazza & Coltheart, 2006). We therefore carried out Experiment 2 to investigate this issue, again with the help of patient R.J. The two theories under investigation (single vs. multiple inhibitory processes) led to different hypotheses: (1)}
If a single inhibitory process was at work, R.J. would present similar deficits (i.e., similar degrees of deficit) in terms of his resistance to visual capture and conflicting response resolution, and (2) if multiple inhibitory processes operate instead, either only one of these abilities should be disturbed (i.e., resistance to capture, since it has already been demonstrated in patient R.J.; Michael et al., 2006; Michael, Kleitz, et al., 2001), or both might be, but to differing degrees (i.e., a single dissociation; Caramazza, 1986).

Method

Participants Patient R.J., a right-handed patient at the Hôpitaux Civils de Strasbourg, was the only case studied in Experiment 2. A full description of R.J.’s history, neuropsychological profile, and well-documented selective loss of inhibition can be found in two previous research reports (Michael et al., 2006; Michael, Kleitz, et al., 2001). At the time of testing (March 2000), R.J. was 29 years old and had completed 11 years of education. Magnetic resonance imaging (Fig. 3) established the presence of a dysembryoplastic neuroepithelial tumor (DNeT) located in the rFo and extending to the proximal insular cortex. R.J. was complaining of difficulties with concentration, but not reporting any memory problem. The neuropsychological examination revealed a dysexecutive syndrome, with inhibitory functions being particularly affected. Verbal and visual memories were not affected. The control group consisted of all those who had taken part in Experiment 1, since they were all well matched with patient R.J. in terms of their age, laterality, and sociocultural level.

Stimuli, apparatus, and procedure These were all as in Experiment 1.

Results and discussion

The R.J.-control comparison was carried out using the $Q$ test (Michael, 2007; Michael, Garcia, Bussy, François-Lion, & Guibaud, 2009; Michael, Relland, Borg, Peyron, & Thomas-Anterion, 2010),2 with Capture Condition (distractor absent vs. present) and Spatial Compatibility (compatible vs. incompatible) as factors. The test involves making adjustments for general slowing, transforming each condition’s RT into $z$ values based on the mean score and standard deviation of the controls, and then comparing the corresponding proportions of participants who obtain less extreme scores than the patient, by means of a $2 \times 2$ factorial design for proportions. Significant results thus suggest a deviation from the pattern obtained with the controls.

The main effect of capture was significant [$Q(1)=34.9, p<.0001$]: R.J. exhibited greater capture effects (distractor absent, 804 ms; distractor present, 1,021 ms; difference, 217 ms) than the controls (controls’ mean difference $\pm$1 SEM, 12±2 ms). The main effect of spatial compatibility was also significant [$Q(1)=20.1, p<.0001$], with a much greater compatibility effect for patient R.J. (compatible, 821 ms; incompatible, 1,005 ms; difference, 184 ms) than for the controls’ performance (controls, 14±4 ms). Excitingly, comparing the extents of the two effects revealed that the effect of capture was greater than that of compatibility [$Q(1)=36.8, p<.000001$; Fig. 4a], contrasting with what we observed among the controls (see Exp. 1). These findings suggest that capture and compatibility are dissociable. A significant Capture×Compatibility interaction was found [$Q(1)=40.9, p<.00001$; Fig. 4b], suggesting that R.J.’s performance deviated from the overall pattern of the controls. The compatibility effect observed in the distractor onset condition (326 ms) was greater than the one observed in the baseline condition (43 ms) to a much larger extent than that observed among the controls (distractor, 15±4 ms; baseline, 13±5 ms; Fig. 2a).

Patient R.J. completed this task without errors.

In combination with Experiment 1, the results suggest that the two inhibitory processes are indeed independent. In fact, this independence was demonstrated through two different methods: the additive-factors method in Experiment 1, and the neuropsychological dissociation in Experiment 2. Yet, with R.J.’s performance, resistance to visual capture was greater when conflicting responses had to be resolved, which suggests that, despite the effects being dissociable, there is a locus of interaction between them. These results take us beyond the single-process/multiple-process distinction and suggest that, in order to function properly, the two independent processes may share a common processing component (Caramazza, 1986; Coltheart & Davies, 2003; Shalllice, 1988). Such a component would be necessary for both resistance to attentional capture and resolving spatial stimulus–response conflicts. On the assumption that this component was damaged, the impairments in both resistance to capture and stimulus–response conflict resolution could be explained.

Experiment 3

One characteristic of inhibition is that it requires cognitive resources to reach high levels of efficiency (Kane, Bleckley, Conway, & Engle, 2001; Kane & Engle, 2003; Michael et al., 2006; Watson & Humphreys, 1997). This has been supported by studies showing that decreased resource availability decreases efficiency in tasks involving conflict resolution, in such a way that distracting signals have enhanced effects (e.g., de Fockert, Rees, Frith, & Lavie, 2001; de Fockert &...
Theeuwes, 2012; Roberts, Hager, & Heron, 1994). According to the resources/capacity theories (Gopher, 1986; Kahneman, 1973; Moray, 1967), performance in one or more tasks suffers when the resource demands placed by the tasks exceed the available supply. One obvious way of investigating whether two phenomena (i.e., capture and compatibility) are distinct is to reduce the available resources and then see whether both are affected in the same way and to similar degrees. A well-documented way of reducing available supply is to ask participants to perform a secondary task. Previous studies have shown that a secondary task increases compatibility effects (Garvey & Knowles, 1954; Hazeltine, Ruthruff, & Remington, 2006; Simon, 1982; Stelzel et al., 2006), but in those particular studies the concurrent task was similar to the primary one. As regards visual capture effects, some indirect evidence has indicated that they may also increase under dual-tasking conditions (de Fockert & Theeuwes, 2012; Michael, Vairet, & Fernandez, 2007). However, whether these changes are similar for both capture and compatibility is as yet unknown, and the aim of Experiment 3 was to find this out. Thus, if they share common cognitive components and neural networks (Bunge, Ochsner, Desmond, Glover, & Gabrieli, 2001), their efficiency would decline in the case of an insufficient resource supply (Hester, Murphy, & Garavan, 2004). To avoid interference with the visual nature of the primary task and its manual/motor output, the nature of the concurrent task was completely different and used different input (i.e., auditory) and output (i.e., verbal) channels.

Method

Participants A group of 31 (four male, 27 female) healthy undergraduate students at the Université Lyon 2 took part in Experiment 3 for course credit. Their mean age was 21.6±3.7 years, and their mean education was 13.3±0.8 years. They were all right-handers according to the Edinburgh laterality inventory, all reported normal or corrected-to-normal vision, and all gave their written consent for their participation.

Stimuli and apparatus The stimuli and apparatus used for the visual task were the same as in Experiment 1. For the auditory task, the stimuli were the numbers 0 to 9. They were recorded in an mp3 file and played back using speakers at a rate of 1/s. The stimuli were arranged in series of ten numbers, with all numbers being presented randomly and once only. Each new...
series started only when the previous one had ended, but the mp3 file contained no marker to signal the end of one series and the beginning of the next. This arrangement prevented participants from developing detection and response strategies.

Procedure The procedure was identical to that of Experiment 1, with one exception: Participants had to complete a concurrent auditory task, the difficulty of which varied: (a) In one condition, they had to listen to the auditory list, but without responding to it; (b) in another, they had to detect a single target (the number 2) by emitting a verbal response (“stop” response); and (c) in a third, they had to detect three targets (the numbers 2, 4, and 6) by emitting the same verbal response. The auditory target(s) appeared in a completely random and unpredictable order. The three degrees of difficulty were presented in three separate blocks, during which participants performed the same visual task (i.e., the visual task remained constant, since the aim was to assess the effects of a secondary task on capture and spatial compatibility). The three blocks were balanced in a Latin-square order across participants. To optimize time-sharing between the visual and auditory tasks (Wickens, 1984), the auditory items were played continuously from the beginning of the block until the end, without interruption. Furthermore, the high throughput of the auditory items (1/s) was aimed at making the task demanding in terms of resources, because it has been shown that if one stream of stimuli is presented at a high throughput rate, another stream cannot be handled efficiently at the same time. The method that we used was therefore a straightforward means of withdrawing resources from the visual task and observing the effects of reduced resource availability. Participants were informed that the two tasks (visual and auditory) were equally important, and that one should not be favored over the other. Their responses were recorded by the experimenter, who sat at some distance from the participant and had the full list of auditory stimuli. On the basis of the results of a pilot study, target detections were considered correct if the response was given within 2 s.

Results and discussion

Auditory task The percentages of hits (correctly detected targets) and false positives observed in the one-item and three-item conditions of the auditory task were subjected to two-tailed Wilcoxon signed rank tests. As expected, the percentage of correct detections was higher in the one-item condition (mean±1 SEM: 95.6±1.2 %) than in the three-item condition (78.8±1.9 %), and the false positive rate was lower in the one-item (0 %) than in the three-item (0.64 %±0.2 %) condition (z=1.65, p<0.05). A signal detection analysis showed that the sensitivity index (d’) was higher in the one-item (4.15±1) than in the three-item (3.0±0.75) condition (z=4.9, p<0.00001). From these results, it was apparent that, as expected, increasing the number of auditory targets increased the task difficulty and, therefore, that increased task difficulty was more demanding in terms of resources.

Visual task RTs of more than 2,000 ms and less than 100 ms were discarded as errors of inattention and anticipation, respectively. Discarded trials accounted for less than 1 % of the total number. An ANOVA was carried out on the correct median RTs, with Capture Condition (distractor absent vs. present), Compatibility Condition (compatible vs. incompatible), and Auditory Task Difficulty (no, one, or three targets) as within-subjects factors. As in Experiment 1, the main effects of capture condition [F(1, 30)=37.1, p<0.00001, η²=.27; distractor absent (mean±1 SEM, 586±20 ms; distractor present, 615±24 ms; difference, 29 ms) and spatial compatibility [F(1, 30)=13.4, p<0.01, η²=.18; compatible, 588±23 ms; incompatible, 612±21 ms; difference, 24 ms] were significant, but the Capture×Compatibility interaction failed to reach significance [F(1, 30)=0.03, p>.95, η²=.0001]. This result exactly matches the results of Experiment 1. Once again, Bayesian analyses (n=341, df effect=2) provided evidence that the interaction was absent, since both the Bayes factor (340.2) and the posterior probability [PH0 | D]=.997 clearly and strongly favored the null hypothesis. The main effect of auditory task difficulty also turned out to be significant [F(2, 60)=15.4, p<0.00005, η²=.53], with RTs lengthening as task difficulty increased (no item, 573±18 ms; one item, 588±23 ms; three items, 640±27 ms). Dual tasking thus resulted in reduced processing speed. The most important finding was that the Auditory Task Difficulty×Compatibility interaction was not significant [F(2, 60)=0.03, p>.97, η²=.001; Fig. 5b], whereas the Auditory Task Difficulty×Capture interaction was [F(2, 60)=4.7, p=.014, η²=.013; Fig. 5a]. Capture increased as auditory task difficulty increased (no items, 19±5 ms; one item, 27±6 ms; three items, 41±7 ms), whereas the compatibility effect remained virtually unchanged (no items, 25±8 ms; one item, 23±7 ms; three items, 24±10 ms; Fig. 5c). The Task Difficulty×Compatibility×Capture interaction failed to reach significance [F(2, 60)=1.33, p>.27, η²=.006]. Bayesian analyses (n=341, df effect=3)5 provided evidence that this three-way interaction was absent, as was shown by both the Bayes factor (2,439:2) and the posterior probability that the absence of this interaction was correct [PH0 | D]=.999.

An ANOVA was also carried out on the percentages of errors, with Capture Condition (distractor absent vs. present), Compatibility Condition (compatible vs. incompatible),

5 According to the null hypothesis, there was no interaction effect; thus, the number of parameters was 0. The alternative hypothesis had three parameters—that is, the difference between the compatible and incompatible conditions in the absence of a distractor could be different from the difference between the compatible and incompatible conditions in the presence of a distractor, and this effect could depend on the difficulty of the auditory task. Therefore, the number of parameters (df effect) that distinguished the null and alternative hypotheses was three.
and Auditory Task Difficulty (no, one, or three targets) as within-subjects factors (Table 1). The main effect of capture condition was significant \( F(1, 30)=5.96, p<.02, \eta^2=.001; \) distractor absent, 5.9 %±.6 %; distractor present, 7.7 %±1.1 %. The main effect of compatibility proved significant \( F(1, 30)=27.8, p<.00002, \eta^2=.01; \) compatible, 3.9 %±.8 %; incompatible, 9.7 %±1.1 %], as did the main effect of auditory task difficulty \( F(2, 60)=6.29, p<.0035, \eta^2=.14; \) no items, 4.9 %±0.8 %; one item, 6.2 %±1.3 %; three items, 9.2 %±0.9 %]. As we observed with RTs, capture did not interact with compatibility \( F(1, 30)=0.35, p>.55, \eta^2=.01 \]. Surprisingly, the Task Difficulty×Capture interaction was not significant \( F(2, 60)=0.37, p>.68, \eta^2=.0 \], but Task Difficulty×
Compatibility was \( F(2, 60)=4.2, p<.019, \eta^2=.001 \). The compatibility effects (incompatible minus compatible) were similar for the detection of no auditory items (5%±1.2%) and one auditory item (3.8%±1.4%), but higher in the case of three auditory items (8.5%±2.0%). No such effect was found for the capture effect (no item, 1.4%±0.8%; one item, 2.6%±1.6%; three items, 1.3%±1.1%). The differential effects of auditory task difficulty on the capture and compatibility effects can be seen in Figs. 5d, E, and F. Finally, the three-way Capture×Compatibility×Task Difficulty interaction failed to reach significance \( F(2, 60)=0.52, p>.50, \eta^2=.001 \).

Experiment 3 replicated and extended the results of Experiment 1. The fact that capture and compatibility did not interact, as well as their lack of interaction with a third factor, namely the difficulty of the auditory task, supports their independence (Sternberg, 1969). The RT analysis revealed that the effects of capture increased with increasing auditory task difficulty, demonstrating that resisting interference is difficult when another task is being performed concurrently. In keeping with previous studies (Garvey & Knowles, 1954; Hazeltine et al., 2006; Simon, 1982; Stelzel et al., 2006), changes in the compatibility effect as auditory task difficulty increased were also observed, but only in the error analysis. The discrepancy observed between RTs and errors cannot be attributed to a speed–accuracy trade-off, since they correlated positively \( r(29)=.51, p<.004 \). A reduction in available resources affects the time needed for resistance to involuntary capture to become operational, while at the same time affecting the accuracy with which a stimulus–response conflict is resolved. Furthermore, to be efficient, resistance to capture requires more resources than does compatibility, since the former was already affected when only one auditory target was present, whereas the latter was not affected until three targets had to be detected.

Thus, as expected, both resistance to visual capture and the resolution of stimulus–response conflicts require resources in order to be fully operational, but the underlying inhibitory processes probably make different uses of the resources needed. Plotting compatibility as a function of capture for each degree of difficulty of the auditory task confirmed such dissociations, since monotonicity was violated (Dunn & Kirsner, 1988; see Fig. 6) for both RTs and error percentages. The fresh question that arises, then, is whether these processes use a common resource pool. This was investigated by means of correlation analyses (Fig. 7) conducted between the capture effect (distractor present minus absent) and compatibility effect (incompatible minus compatible) for each degree of auditory task difficulty. The analysis of error percentages revealed nothing, but the RT analysis did. Matching the results of Experiment 1, no significant correlation was found between capture and compatibility when participants performed the visual task with no concurrent auditory task [i.e., no-item condition; \( r(29)=−.19, p>.30 \)]. However, with one auditory target a significant negative correlation was found \( r(29)=−.37, p<.04 \), which became even stronger with three auditory targets \( r(29)=−.49, p<.005 \). This growing correlation between capture and compatibility suggests that they share a common resource pool. The fact that the correlations are negative means that when capture increases, spatial-compatibility effects decrease, and vice versa, just as if resources were used to control the former at the expense of the latter. It is as if resources were used for either one or the other, in order to find a balance between them. So, if with RTs the difficulty of the auditory task interacted with capture but not compatibility, this is probably because participants managed to keep constant their ability to resolve conflicting responses efficiently, even if this meant that resistance to capture was reduced as a result. This was also confirmed, albeit the other way around, through the error analysis.

General discussion

Three experiments were conducted to investigate whether a single, general inhibitory process or multiple independent inhibitory processes operate (e.g., Aron, 2007; Dagenbach & Carr, 1994; Kok, 1999; Nee et al., 2007). With that aim in mind, we used variants of a previously published paradigm (Michael & Buron, 2005; Michael, Kleitz, et al., 2001) to investigate two effects linked to inhibitory processes: resistance to visual capture by task-irrelevant onsets, and resolution of conflicting responses arising due to the task-irrelevant spatial location of the target (de Fockert & Theeuwes, 2012; Fan et al., 2003; Kok, 1999). Two categories of findings can be sketched out, with signs of dissociable processes in the first, and signs of links between otherwise dissociable processes in the second.

Signs of dissociation

Experiments 1 and 3 clearly showed that the abrupt onset of a distractor did not affect the speed or accuracy with which a conflicting response was resolved, despite both aspects of conflict resolution individually influencing performance. According to Sternberg (1969), such an additive effect is suggestive of the independence of the underlying computations, a suggestion backed up by the absence of any linear link between the effects of an onset distractor and those of spatial compatibility in situations in which no concurrent auditory task was performed (i.e., Exp. 1). Besides, in Experiment 3, the inclusion of a concurrent auditory task did not affect this pattern (i.e., absence of a three-way interaction), which was, once again according to Sternberg (1969), suggestive of independence. Instead, Experiment 3 demonstrated that dual
tasking influenced the effects of an onset distractor and those of spatial compatibility differently. Finally, capture and compatibility proved to be clearly and strongly dissociable in patient R.J.’s performance (Exp. 2), in spite of both being affected. When combined with the aforementioned findings, this single dissociation cannot be attributed to a resource artifact (i.e., that it is more difficult to resist visual capture than to resolve conflicting responses; Shallice, 1979). The conclusion that can be drawn from this is therefore that resistance to capture and the resolution of stimulus–response conflicts are independent, as suggested by the multiple-inhibitory-processes hypothesis (Dagenbach & Carr, 1994; Kok, 1999; Kramer et al., 1994; Nee et al., 2007). A similar independence has already been suggested between inhibition involved in Stroop-like tasks and spatial-compatibility tasks (Fan et al., 2003; Kornblum, 1994; Simon & Berbaum, 1990).

Signs of association

The first finding suggesting a possible degree of association between resistance to visual capture and the resolution of conflicting responses was that both were affected in patient R.J.’s performance (Exp. 2). This is critical, because the same damaged brain area, the rFO, disturbed two otherwise

**Fig. 6** Dunn and Kirsner’s (1988) analysis of the results (A. response times, B. error percentages) obtained in Experiment 3. The effect of capture (distractor present minus absent) is plotted against the effect of compatibility (incompatible minus compatible) as a function of the difficulty of the concurrent auditory task (no, one, and three auditory targets). Note that the monotonicity of the function is violated, suggesting that capture and compatibility rely on functionally independent processes.

**Fig. 7** Results of Experiment 3. Correlation between the main effects of capture (distractor present minus absent) and compatibility (incompatible minus compatible) as a function of the difficulty of the concurrent auditory task (no, one, and three auditory targets). Note the negative and increasingly strong correlations. Asterisks denote significant correlations: *p<.05; **p<.005
independent inhibitory processes, consistent with the view that the rFO—and the IFG in general—is part of the distributed brain network underlying inhibition (Garavan et al., 1999), independently of the task (Chambers et al., 2009; Leung & Cai, 2007; Levy & Wagner, 2011; Wager et al., 2005; Xue et al., 2008). It also back up our previous studies (Michael et al., 2006; Michael, Kleitz, et al., 2001), in which patient R.J. exhibited deficits in several tasks involving inhibition. In Experiment 2, we also observed that the effects of an onset distractor were greater when the stimulus location and target feature were in conflict. Therefore, the additive effects found in the controls’ performance (Exps. 1 and 3) were transformed into an interacting pattern in patient R.J.’s performance. Combined with the aforementioned findings, according to which the two inhibitory processes are independent, this suggests the existence of shared, albeit distinct, processing components (Caramazza, 1986). On the assumption that this is the processing component that was damaged, both impaired resistance to capture and the resolution of conflicting responses can be explained without the need to refer to the existence of any damage in each and any of the two independent inhibitory processes. This is backed up by another finding suggesting that the two processes may have something in common: the negative and increasingly strong linear link found between them as the difficulty of performing a concurrent auditory task increased (Exp. 3). Since dual tasking reduces available cognitive resources (Gopher, 1986; Kahneman, 1973), such a finding suggests that such resources may be used either to resist capture or resolve conflicting responses, as if participants made an attempt to strike a balance between these processes. When resources are used for the former process, they seem to be taken from the latter, and vice versa. This, of course, confirms that there is a hierarchy between resources and inhibition, with inhibition depending on the integrity and availability of resources (Kane et al., 2001; Watson & Humphreys, 1997). Whether it is sensory or motor, inhibition needs resources to function properly (Kane et al., 2001; Michael et al., 2007; Simon, 1982), and the results of Experiment 3 suggest that the two presumably independent processes use a common resource pool (Wickens, 1984).

The shared component

The results of the present study suggest at least two independent inhibitory processes, which share a common processing component. This is in line with some previous investigations that had pointed out that different inhibitory tasks may be completed through only partially independent processes. This means that a single component may be used by otherwise different processes (Liu, Banich, Jacobson, & Tanabe, 2004). The fact that capture and compatibility did not interfere with each other (Exps. 1 and 3) intimates that the putative common component is not a resource pool (Hester et al., 2004). The degree to which two tasks interfere with each other is determined by the degree to which they compete for common cognitive and neural components (Fusser et al., 2011; Kinsbourne & Hicks, 1980; Mayer et al., 2007; Wickens, 1984). Quoting Sternberg (1969), “in a task where process a has to accomplish more, less capacity is made available for process b. If more is then also demanded of process b, its duration will increase more than if the available capacity had been greater” (p. 288). So, if the shared component were a resource pool, manipulating resource availability would lead capture and compatibility to interact. Yet, Experiment 3 failed to evidence such an interaction, and therefore the putative common component is not a resource pool.

What could this component be, and how would it work? It has been noted that conflict detection, presumably involving the anterior cingulate cortex (Botvinick et al., 2001; Botvinick, Cohen, & Carter, 2004), is one of the functions capable of regulating the extent to which attentional control should be engaged to resolve competing representations (Hester et al., 2004). Following conflict detection, lateral areas of the prefrontal cortex underlying attentional control would be engaged to reduce conflict (Carter & van Veen, 2007). Such mechanisms would thus determine and engage the amount of resources or effort (Kahneman, 1973) necessary for efficient conflict resolution. Therefore, developing and maintaining successful inhibitory control under increasing task demands would depend on the distribution of available resources (Kane et al., 2001; Kane & Engel, 2003; Michael et al., 2006; Watson & Humphreys, 1997). This is consistent with brain-imaging data showing that when greater effort is needed for inhibition to be successful, greater activity in inhibition-related regions is observed (Durston et al., 2002; Garavan et al., 1999; Hester et al., 2004). Greater activation of a process dealing with the resolution of one kind of conflict may be achieved by allocating a greater amount of resources to it, leaving fewer resources available for processes dealing with the resolution of other kinds of conflict. This is consistent with our finding that the correlation between capture and compatibility grew negatively as the demands of a secondary auditory task increased (Exp. 3), suggesting that more resources were used for the former at the expense of the latter. Consequently, one possible function of the common component detected in the present study, and probably subserved by IFG, would be to choose which inhibitory process would need greater activation—that is, to choose the process to which resources would be assigned. This inhibition prioritization hypothesis is consistent with the findings that the IFG is

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2 Since they are not based on a resource pool, the results obtained by patient R.J. in Experiment 2 (but also in the previous studies: Michael et al., 2006; Michael, Kleitz, et al., 2001) cannot be attributed to pathologically reduced resources.
almost constantly activated in tasks involving inhibition (e.g., Aron, 2007; de Fockert & Theeuwes, 2012; Nee et al., 2007; Wager et al., 2005; Xue et al., 2008), that lesions of this area produce disturbances in a large variety of tasks involving inhibition (Exp. 2; see also Aron, 2007; Hodgson et al., 2007; Michael et al., 2006), and that increasing difficulty in tasks involving inhibition correlates with increasing activation of the IFG (de Fockert & Theeuwes, 2012; Durston et al., 2002; Garavan et al., 1999). A similar idea was put forward by Stelzel et al. (2006), who suggested that a generalized function of the inferior frontal areas would be to manage and coordinate interference between competing processes. How the choice of the inhibitory process to feed is accomplished remains unclear. At a neural level, this probably occurs through modulation of areas involved in more specific inhibitory functions. At a cognitive level, it is probably accomplished by estimating whether or not increased activation would be successful. For instance, when increasing the amount of resources necessary to inhibit highly salient items proves pointless (Michael, Boucart, et al., 2001), resources could be allocated to another process and used, for example, to resolve conflicting responses. Some preliminary results from our laboratory back up this modus operandi, but further investigation will be required.

Alternatives: There is no such thing as inhibition

Whether performance in tasks involving interference resolution can be explained by referring to constructs like inhibition is subject to debate. It has been suggested that when current processing turns up two or more paths that we might follow, we must choose, and this choice adds to our processing (MacLeod, 2007; MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003). Even though this debate goes way beyond the scope of the present study, we admit that interference resolution may also be achieved through the facilitation of relevant features instead of the inhibition of irrelevant ones. Besides, in some models of conflict monitoring (i.e., Botvinick et al., 2001; Botvinick et al., 2004), the actual adjustments involve changing spatial-attention settings or the activation of task-demand units, instead of inhibition. For instance, residual attentional capture could be due to the time needed to choose which one of two competing salient locations (that of the target or that of the distractor) has to be enhanced and prioritized, instead of which one has to be inhibited. In such a case, the results of patient R.J. would reflect failures to choose or to enhance the relevant location. Yet, in a previous investigation (Michael et al., 2006) we found that this patient could set priorities and could correctly select target locations. This enhancement of spatial locations was still correct, even when competing items considerably slowed its response speed. On the other hand, the negative correlation between capture and compatibility found in Experiment 3 could reflect the fact that when one relevant feature is enhanced, the other is left behind. If this is what it is predicted by the “enhancement” hypothesis, then such a negative correlation should also be found in the absence of a concurrent task (i.e., in Exp. 1 and the no-auditory-target condition of Exp. 3). In any case, even if most of our results were compatible with the literature on inhibitory processes, we leave open the possibility that parts of the results might be explained by other theoretical constructs.

Limits of this study

The major limit of the present study is that some inferences from Experiments 1 and 3, drawn from the absence of significant interactions between capture condition and compatibility, may be considered uncertain, and thus confidence in any substantive interpretation of a null result may be low. Indeed, in both experiments, the interaction effects were very small (Exp. 1, 2±27 ms; Exp. 3, 0±46 ms), and the related effect sizes were not far from zero (Cohen’s $d=0.074$ and $d=0.0$, respectively). Provided a power of 80% ($\delta=2.8$) to detect a medium effect size ($d=0.5$), the sample size needed to detect a reliable Capture×Compatibility interaction would be 31. Given that, in the present study, the sizes of the samples were 33 and 31, we conclude that there was enough power to avoid a Type II error. Further analyses based on Bayes’ theorem were carried out in which the null and alternative hypotheses were compared. These analyses provided very strong evidence in favor of the null hypothesis (i.e., that the interaction between capture and compatibility was, indeed, absent). We are therefore confident that, in both Experiments 1 and 3, the presence of a pattern combining main effects of capture and compatibility and the absence of an interaction tell a quite coherent story, based on the additive-factors logic (Sternberg, 1969).

Conclusions

In the present study, we aimed to contribute to the debate about the multiplicity of inhibitory processes. Our results support the existence of at least two dissociable processes, but also that of a processing component that they both share. This is in line with a number of brain-imaging and brain lesion studies. Our findings lend support to the idea that this component contributes to the functioning of both inhibitory processes, probably by choosing which inhibitory process would need greater activation under certain circumstances. Yet, whether this component participates to the same degrees in the functioning of each of these processes, and how it proceeds to the selection of the process to activate, remains unclear.

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References


inferior prefrontal cortex revealed by event-related functional MRI. Brain, 122, 981–991.


