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Representations in working memory yield interference effects found with externally-triggered representations

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ABSTRACT

An act as simple as flicking a switch involves various stages of processing. Each stage is susceptible to interference from competing representations/processes. Interference at different stages of processing (e.g., *perceptual* stages versus *response selection* stages) leads to distinct behavioral, neural, and subjective effects. In the flanker task, for instance, one responds to a visual target and disregards flanking 'distractors.' Theoretically-predicted interference (increased response times, error rates, and subjective 'urges to err') is stronger when distractors and targets are associated with different actions (*response interference*) than when they look different but are associated with the same action (*perceptual interference*). Extant versions of the task tax working memory (WM) minimally, but many everyday actions (e.g., searching for keys or holding one's breath) require more WM-based control. To illuminate this uncharted area, we examined the nature of interference in *delayed action tasks*, which rely on WM. We found that systematic interference arises even when action-related representations are, not triggered solely by external stimuli, but actively held in WM. We discuss these findings with increased emphasis on the under-explored subjective effects of different kinds of interference. The implications of these findings for the study of action production, WM, and conscious processing are entertained.

1. Introduction

An act as simple as flicking a light switch involves various stages of processing (e.g., encoding, response selection, and response execution; Hommel & Elsner, 2009), each of which is susceptible to interference from competing representations/processes (Desimone & Duncan, 1995; Di Lollo, Enns, & Rensink, 2000; Eriksen & Schultz, 1979; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001). Interference at different stages of processing (e.g., *perceptual* stages versus *response selection* stages) leads to distinct behavioral, neural, and subjective effects (Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Eriksen & Schultz, 1979; Mattler, 2005; Morsella, Wilson, et al., 2009; van Veen et al., 2001). Of all these consequences, the least is known about the subjective effects, that is, the subjective 'tuggings and pullings' of response interference. These subjective effects are the primary focus of our experimental project (as in Morsella, Gray, Krieger, & Bargh, 2009; Morsella, Wilson, et al., 2009). To appreciate this one, under-explored aspect of response interference, it is important to first understand the nuts and bolts of response interference more generally.

1.1. External distractors interfere with responding to external targets

Systematic effects from interference at different stages of processing have been most clearly demonstrated in the classic Eriksen flanker paradigm (Eriksen & Eriksen, 1974). In one version of the task (Eriksen & Schultz, 1979), participants are trained to press one button with one finger when presented with the letter S or M and to press another button with another finger when presented with the letter P or H. After training, participants are then instructed to respond to the stimulus presented in the center of an array (e.g., SSPSS, SSMSS, targets underscored) and to disregard the 'flanking' distractors (i.e., the Ss). Of all the flanker conditions, measures of interference such as response times (RTs), error rates, and self-reported 'urges to err' are lowest in the *Identical* condition, where flankers and targets are identical, as in SSSSS (Eriksen & Schultz, 1979; Morsella, Wilson, et al., 2009). (Urges to err, a subjective effect, are obtained simply by asking participants after each trial, "How strong was your urge to make a mistake?", which they rate on an 8-point scale, in which 1 signifies "almost no

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urge" and 8 signifies "extremely strong urge.") In this paradigm, it is well established that interference is greater when distractors are associated with a response that is different from that of the target (*response interference* [RI]; e.g., SSPSS) than when distractors look different from targets but are associated with the same response (*perceptual interference* [PI]; e.g., SSMSS; Morsella, Wilson, et al., 2009; van Veen et al., 2001).[1]

Psychophysiological research shows that, in a response interference paradigm such as the flanker task, competition involves simultaneous activation of the brain areas associated with the target-related and distractor-related responses (DeSoto, Fabiani, Geary, & Gratton, 2001). This appears to be a case of 'activation before selection' (Morsella, 2009).[1] Accordingly, neuroimaging has revealed that, although both RI and PI are associated with interference when compared to the Identical condition, RI is the condition that activates the anterior cingulate cortex (ACC), a brain region located in the frontal lobe that is interconnected with many motor areas and is believed to be involved with response conflict and response selection (Botvinick, 2007; Brown & Braver, 2005; Cohen, Dunbar, & McClelland, 1990; Crick, 1995; MacLeod & McDonald, 2000; Mayr, 2004; Mayr, Awh, & Laurey, 2003; van Veen et al., 2001).

Regarding the subjective effects of interference, that RI leads to the strongest subjective effects (e.g., 'urges to err' or 'perceptions of interference'; Morsella, Wilson, et al., 2009) has been explained by theoretical developments about the primary function of conscious/controlled processes in action production (cf., Morsella, 2005; Morsella, Berger, & Krieger, 2011; Pashler, 1995; Sanders, 1983). Importantly, one of these theoretical developments (Morsella, 2005) was intended to explain a different class of phenomena, such as why skeletomotor action conflicts (e.g., holding one's breath) reliably perturb consciousness but other kinds of conflicts, such as intersensory conflicts (e.g., the McGurk effect; McGurk & MacDonald, 1976) and conflicts involving smooth muscle, do not (for further explanation, see General Discussion and Morsella, 2005; Morsella, Gray, Krieger, & Bargh, 2009; Morsella, Berger, & Krieger, 2011).

Data suggest that the trial-by-trial subjective effects (e.g., urges to err) are not simply artifacts arising from participants observing their own RTs. For example, these subjective effects are still robust in a flanker-like interference paradigm (Morsella, Wilson, et al., 2009) in which participants are instructed to withhold responding for over a second, which eradicates RT effects (Eriksen & Schultz, 1979). Moreover, the effects are present when participants sustain incompatible intentions (e.g., to point left *and* right) in a motionless state in which no response is required or emitted (Morsella, Gray, Krieger, & Bargh, 2009). In addition, though post-error corrections in interference paradigms involve improved performance (e.g., faster RTs) on trials following a trial involving response interference (e.g., an incongruent trial), reported urges to err actually increase on such a trial, which has been explained as a difference between *implicit* measures of performance (e.g., RT) and *explicit* measures (e.g., self-reports about task difficulty; A. Etkin, personal communication, July 1, 2009). Moreover, it has been claimed that the two measures reflect the functioning of different systems, one being implicit and one being explicit (Etkin, Prater, Hoeft, Menon, & Schatzberg, 2010; Goodale & Milner, 2004; Gyurak, Gross, & Etkin, 2011; Morsella, Berger, & Krieger, 2011; Schacter, 1996).

1.2. Do external distractors interfere with responses relying on items held in working memory?

The findings reviewed above stem from paradigms in which targets and distractors are visually available as stimuli that are present in the external environment. In the flanker task, for example, both targets and distractors are presented simultaneously as physical stimuli comprising part of the visual scene. In everyday life, however, seldom is it the case that planned action is driven wholly by representations activated only by external stimuli. Many actions, such as goal-directed actions, are guided by representations that are generated internally (Miller, Galanter, & Pribram, 1960; Neisser, 1976). Quotidian acts such as voluntarily holding one's breath, searching for one's car keys, or holding a telephone number in mind demand that representations be held actively in mind with minimal aid from the external environment. These acts usually involve *working memory* (WM), which has been defined as a temporary, capacity-limited storage system under attentional control, used to intentionally hold and manipulate information (Baddeley, 1986, 2007).

Recent theoretical developments have revealed that WM is intimately related to complex thought and to action control, as is evident in the title of the book *Working Memory, Thought, and Action* (Baddeley, 2007), a synthesis of WM research by one of the pioneers of this area of study. From this standpoint, the acts of voluntarily holding one's breath, looking for one's keys, or holding a telephone number in mind can be considered cases of *WM-based action control*, because WM is essential for carrying out these goal-driven actions. But what is the nature of interference (including its subjective effects) in such a form of control?

The potential interference effects between representations involving WM have been construed as a form of *inter-representational dynamics* (Morsella, Zarolia, & Gazzaley, 2012). Regarding these dynamics, it has been established that the similarity or dissimilarity between external distractors and memoranda (the information held in mind) can lead to systematic effects, as in the case of the well-known *similarity effect* (cf., Baddeley, 2007), in which distractors that are similar to items held in WM are more likely to interfere with WM performance than distractors that are dissimilar and less confusable. Apart from the similarity effect, however, the nature of the interference effects mentioned above (i.e., RI versus PI) has remained under-explored with respect to WM-based action control. To date, the general differences between regular interference on action production and interference in WM-based action control remain unknown.[2]

Sustaining the activation of internally-generated representations is an effortful process, requiring that top-down activation strengthen one representation (e.g., the target) over another (e.g., the flankers).

[1] The developers of the flanker task have attributed RI to the automatic activation of response codes by distractors (Coles et al., 1985; Eriksen & Eriksen, 1974; Eriksen & Schultz, 1979). They have explained this automatic activation by appealing to the notion of *continuous flow* (Eriksen & Schultz, 1979), a notion that is based on observations of the basic neurophysiological characteristics of perceptual processing (Ganz, 1975) and that is similar to that of *cascade* processing (McClelland, 1979). From the standpoint of continuous flow, activation cannot help but flow from one stage of processing (e.g., perceptual) to the next (e.g., motor preparation), even when the previous stage has not concluded its analysis. (See review of continuous flow processes in Levine, Morsella, & Bargh, 2007.) It is important to note that RI effects have also been explained successfully by *serial models* of processing (e.g., Levelt, 1989; Levelt, Roelofs, & Meyer, 1999), in which activation flows to the next stage of processing only after the present stage has completed its analysis, and by models in which perception-and-action occur within the same stage of processing (Hommel et al., 2001). (Adjudicating among the models regarding how activation flows in the nervous system is beyond the purview of the present project; for some evidence for continuous flow models, see Coles et al., 1985; Morsella & Miozzo, 2002; Navarrete & Costa, 2004.)

[2] One difference between externally-elicited and internally-generated representations is that the latter is usually more effortful. There is a performance benefit in having external stimuli sustain (or 'scaffold'; Hoover & Richardson, 2008) the activation of internal representations. For example, recent research suggests that mental control can be influenced by the external stimuli composing one's current environment (Levine et al., 2007). In such a situation, external stimuli can activate action-related *sets* (Levine et al., 2007; Morsella, Larson, Zarolia, & Bargh, 2011) and can help hold information in mind, making the world a kind of 'external memory' (O'Regan, 1992), to which some of the burden of mental control can be relegated (Arkin, 1998; Brooks, 1991; Clark & Chalmers, 1998; Hoover & Richardson, 2008). Thus, perceptual stimuli arising from the external world (or even from one's own body) can be used as cues that facilitate mental control and cognitive processing more generally (Ballard, Hayhoe, Pook, & Rao, 1997; Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001; Morsella & Krauss, 2004).

This has been characterized as a special case of 'refreshing' (Johnson & Johnson, 2009), the component process in WM that reactivates a recently activated representation (Raye, Johnson, Mitchell, Greene, & Johnson, 2007). Specifically, refreshing is "the act of thinking of, or foregrounding, a representation of a thought or percept which was activated just a moment earlier and has not yet become inactive" (Johnson & Johnson, 2009, p. 174). There is evidence that distinct frontal regions are involved in the refreshing of different kinds of representations. For example, different regions of dorsolateral prefrontal cortex are activated for refreshing words versus objects (Johnson, Raye, Mitchell, Greene, & Anderson, 2003). Although it is a minimal form of cognitive control (Raye et al., 2007), refreshing is nonetheless an effortful executive process.

1.3. Outstanding questions

To our knowledge, no WM study has yielded the kinds of systematic interference found with the flanker conditions Identical, PI, and RI. Moreover, although research has illuminated the interference dynamics between (a) targets and distractors that are presented externally, and (b) items held only in WM (e.g., the *word-length effect*; Baddeley, 2007), no study to date has examined the interplay between both kinds of interference, that is, between representations triggered by external stimuli and representations actively held in WM. Do established interference effects arise when conflict is between (a) representations that are externally elicited and (b) representations that are internally sustained?

To address these and other questions, we developed *delayed action tasks* (Curtis & D'Esposito, 2009; Müsseler & Hommel, 1997a) based on the flanker task and incorporating subjective measures (i.e., urges to err), which are the primary focus of our research. In these tasks, participants must hold an action plan in mind for a span while overcoming the influence of distractors. (Several experiments have required participants, during a delay, to hold in mind action plans that involve stimulus–response mappings; cf., Müsseler & Hommel, 1997a, 1997b; Müsseler, Wühr, & Prinz, 2000.) In Experiment 1A, participants were presented with a target from the flanker task (an S, M, P, or H) and instructed to delay responding (7 s) until seeing a small dot on the center of the screen. Participants were told that this dot may be surrounded by two letters, but that the flanking letters should be disregarded. The dot was always flanked by two identical letters (S, M, P, or H); on a given trial, an S may be followed by S • S (Identical), M • M (PI), P • P (RI), or the other permutations. Experiment 2 was a necessary replication in which the action prompt was itself a letter, presented by itself. The appearance of this distractor letter served to prompt participants to execute the response associated with the target that had appeared 7 s beforehand. In this case, other aspects (e.g., the identity) of distractors should be ignored.

Because delaying the onset of distractors eliminates flanker interference in standard versions of the flanker task in which all stimuli are sustained by the external world (Eriksen & Schultz, 1979), the *ballistic hypothesis* (Lashley, 1951; cf., Hommel, 1996) predicts that, with a response preparation spanning 7 s and with response certainty (i.e., subjects know exactly which action will be executed when cued to act), any distractor-based interference should be eliminated. This has been predicted by Berlucchi, Crea, Di Stefano, and Tassinari (1977). Only a few studies (e.g., Hommel, 1996) have shown interference effects under conditions of response certainty and with participants having an ample response preparation span. In one experiment, Hommel (1996) had participants press one of two buttons (e.g., the left button) after being presented with a cue (e.g., an arrow pointing left). After seeing the arrow, however, participants had to delay their response for a span (400 ms to 1400 ms) until seeing a 'go' signal. Participants were instructed that the nature of the go signal should be disregarded. At times, the signal happened to be an arrow pointing left or an arrow pointing right. Despite response certainty and the response preparation span, Hommel (1996) still found compatibility effects: When the go signal happened to be congruent with the desired action, facilitation was observed. As discussed in the General Discussion, our delayed action paradigm builds on this study in several ways, including by having the three interference conditions of the flanker task, a much longer span for response preparation, and subjective measures.

1.4. Predictions

Our aim was to assess whether, in a delayed action task, the patterns of subjective and behavioral effects from Identical, PI, and RI resemble what has been observed in standard ('non-working memory') response interference paradigms. We predicted that the PI and RI conditions should lead to the same pattern of behavioral and subjective results that has been found with external stimuli. Regarding our aims, it is important at this point to emphasize that much of what is presented here, such as the holding in mind of stimulus–response mappings or the interference from action-related distractors presented during a delay before action execution, has been investigated and documented heretofore (e.g., Baddeley, 2007; Hommel, 1996; Müsseler & Hommel, 1997a, 1997b; Müsseler et al., 2000). What is novel in our approach is, first and foremost, the investigation of the under-explored subjective aspects of the responses in such a response interference paradigm (cf., Morsella, Wilson, et al., 2009) and, second, the inclusion of the three levels of interference (i.e., Identical, PI, and RI) into a delayed action task.

2. Experiment 1A

2.1. Method

2.1.1. Participants

San Francisco State University (SFSU) undergraduates ($n = 52$) participated for class credit.

2.1.2. Procedure

Participants first provided informed consent about the study, which was approved by the internal review board of SFSU. Based on the procedures of van Veen et al. (2001), participants were first trained in 32 trials to press specified computer keys when presented with certain letters (48 point Helvetica, $0.89° \times 1.07°$) in the center of a computer screen: When presented with S or M, they pressed a key (occupying the "4" position on the number pad of the keyboard) with their right index finger; when presented with a P or H, they pressed the adjacent ("5") key with their right middle finger. Participants were instructed to respond as quickly and as accurately as possible. Occupying less than 2 cm^2, each target was presented 8 times in random order. Stimuli for this and all subsequent experiments were presented on a white background of a 50.8 cm Apple iMac computer with a viewing distance of approximately 48 cm. Stimulus presentation was controlled by PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993).

In the critical trials ($n = 96$), participants were presented with a target stimulus (the letters S, M, P, or H) and asked to delay responding (7 s, based on Gazzaley, Cooney, Rissman, & D'Esposito, 2005) until the onset of another stimulus, a small dot ($.34° \times .34°$) in the center of the screen. Participants were told that this dot may be surrounded by two letters, but those letters, and their identities, should be disregarded. The dot was always flanked by two identical letters (S, M, P, or H), each spaced approximately 0.75° horizontally on each side ($3.18° \times 1.07°$ for the whole stimulus array). (Before commencing the critical trials, participants performed two practice trials with Xs as flanking distractors.) In the Identical condition, the target and distractor letters were equivalent (e.g., S followed by S • S; 48 trials, 12 replications for each letter). In the PI condition, targets and distractors were associated with the same response but different letters (e.g., S followed by M • M; 24 trials, 6 replications of each possible combination). In RI, targets and distractors were associated with different responses and different letters (e.g., S followed by P • P; 24 trials, 6 replications of four possible combinations). The stimuli from these 96 trials were presented in random order. Each trial began with a ready prompt (?). When ready, participants pressed the space bar with their left hand. The target (see Fig. 1), preceded by a blank screen (300 ms) and a fixation cross (500 ms), appeared for 1 s and was followed by the delay period (7 s). After the response and 2 s, participants were asked, "How strong was your urge to make a mistake?", which they rated on an 8-point scale, in which 1 signified "almost no urge" and 8 signified "extremely strong urge."

The data from 8 of the 52 participants were excluded from analysis because the participants failed to follow the task instructions. Regarding the remaining RT data, trials in which participants erred (43 [1.02%] of 4224 trials) were excluded from the RT analysis. In addition, based in part on the procedures of Morsella, Wilson, et al. (2009), van Veen et al. (2001), and Woodworth and Schlosberg (1954), RTs below 200 ms and exceedingly long responses (RT ≥ 2 s) were excluded from analysis, resulting in the loss of 76 (1.8%) out of 4224 trials. Because of the removal of erroneous trials and RT trimming, the total RT data removed from the data of the 44 participants was 109 (2.6%) of 4224 trials. Regarding the subjective ratings, typographical errors and omitted responses resulted in the loss of 33 (0.78%) out of 4224 urge data points.

2.2. Results

2.2.1. Error analysis

The mean error rate per participant was .01 (SD = .02). Descriptive statistics of errors per condition are presented in Table 1. Errors occurred in 43 (1.02%) of 4224 trials. ANOVA revealed a significant effect of interference condition, $F(2, 86) = 6.172$, $p = .003$ ($\eta_p^2 = .13$). Planned comparisons revealed that all the contrasts between conditions were significant ($ts > 2.3$, $ps < .05$) except the contrast between Identical and PI, $t(43) = .726$, $p = .47$. Analysis on arcsine transformations of the data also revealed that condition had a significant effect on error rates, $F(2, 86) = 8.26$, $p = .0005$. (Arcsine transformations are often used to statistically normalize data that are in the form of proportions.) In this analysis, the contrasts involving RI were significant, and, unlike with the untransformed data, the difference between Identical and PI approached significance, $t(43) = 1.93$, $p = .06$.

Table 1
Mean response time (ms), error rate, and urges to err as a function of condition in Experiment 1A.

Condition	Response times		Error rates		Urge to err	
	Mean	*SEM*	Mean	*SEM*	Mean	*SEM*
Identical	539.22	23.18	.007	.002	1.61	.16
Perceptual interference	560.52	25.21	.005	.003	1.84	.18
Response interference	588.52	31.36	.019	.006	2.16	.18

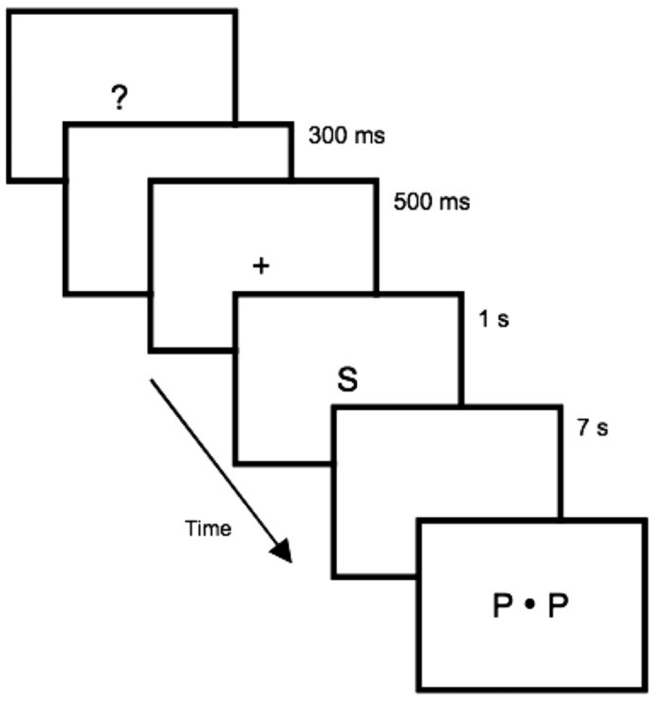

Fig. 1. Time course of stimulus events in Experiment 1. Not drawn to scale.

2.2.2. Subjective effects

The pattern of results of urges to err resembled that of mean RTs in standard flanker tasks (Table 1), revealing a significant effect of condition, $F(2, 86) = 27.74$, $p < .0001$ ($\eta_p^2 = .39$), with the contrasts between the conditions all being significant, $ts > 3.6$, $ps < .001$.

2.2.3. Response times

The mean RT per participant was 555.74 (SEM = 24.60). Mean RTs for the three conditions (Identical, PI, and RI) followed the pattern typically seen in the traditional flanker paradigm (Table 1). ANOVA revealed that interference condition produced a significant effect, $F(2, 86) = 8.50$, $p = .0004$ ($\eta_p^2 = .17$). Planned comparisons revealed that all the contrasts between conditions were significant, $ts > 2.1$, $ps < .05$. The same pattern of results, including significant ($ps < .05$) contrasts between all conditions in the planned comparisons, is obtained when including trials in which participants made an incorrect response, $F(2, 86) = 8.60$, $p = .0004$ ($\eta_p^2 = .17$).

2.2.4. Correlation between subjective and behavioral effects

An analysis including erroneous trials revealed that RT correlated with urges. The mean correlation coefficient, $r = .28$, is significant (Fisher's r to z, $p < .05$) for the number of observations (96) per participant. The correlational trend was also found within condition ($r_{Identical} = .23$, $r_{PI} = .28$, and $r_{RI} = .35$). These data suggest that participants may have been basing their judgments on observing their own RTs.

2.2.5. Discussion

Traditional perceptual and response interference, including their behavioral and subjective aspects, were obtained with our delayed action task, despite (a) response certainty, (b) the long duration of response preparation, and (c) that participants did not need to identify the identity of the distractor to respond accurately. The findings seem to counter the prediction based on the ballistic hypothesis, in which, with response certainty and a response preparation span of 7 s, any distractor-based interference should be eliminated.

3. Experiment 1B

3.1. Replication with two memoranda and response uncertainty

One could argue that the term 'inter-representational dynamics' should not be applied to Experiment 1A, because, for the majority of the duration of the trial, participants held only one action-related representation in mind. During the trial, it was only when the prompt appeared at the end of the trial that competing representations could be activated simultaneously. With this in mind, and to replicate our effects in a more challenging paradigm with less response certainty, we performed additional data collection with a slightly different paradigm. Here participants were instructed to hold two stimuli (e.g., the 'S' and 'P' of the flanker task) in mind until a cue prompted them to respond to one of the two stimuli. Specifically, participants were told that they would be presented with two letters at once, with one letter presented above the other. Participants were told that the letters would appear briefly (1 s), disappear, and, then, after a delay (7 s), a dot would appear in one of the two positions where one of the letters had been presented. Participants were instructed to execute the action associated with the letter that previously occupied that position. To perform this task successfully, participants had to keep information in mind for 7 s, through a rehearsal process such as refreshing. In this way, participants held two representations in mind, representations that would lead to PI or RI, dynamics that should lead to different behavioral and subjective effects.

Although finding a pattern of results similar to that of Experiment 1A would provide additional convergent evidence for the conclusions reached about our delayed action paradigm, the present task suffers from a potential limitation that is not shared by Experiment 1A: Under certain assumptions, the RI condition can be construed as being a 'choice-response time task,' whereas the PI and Identical conditions could be construed as being 'simple response time tasks.' In the literature, the latter is associated with shorter RTs than the former. Because of this potential limitation, we treat these data as supplementary and not as data that can be used to reach conclusions by themselves.

3.2. Method

3.2.1. Participants

SFSU undergraduates ($n = 18$) participated for class credit.

3.2.2. Procedure

After the training procedure of Experiment 1A, participants were told that they would be presented with two letters at once, with one letter presented above the other (Fig. 2). The letters were presented in a vertical orientation, and not with one letter to the left or right of the other, to eliminate spatial compatibility artifacts, the kinds of effects found in the Simon task (Simon, Hinrichs, & Craft, 1970). Participants were told that the letters would appear briefly, disappear, and then, after a delay, a dot would appear in one of the two positions where one of the letters had been presented. Participants were instructed to perform the action associated with the letter that previously occupied that position. Examples were demonstrated onscreen so that participants understood the protocol. Before test, participants were reminded to respond as quickly and as accurately as possible. The delay between the presentation of the letters and the dot was 7 s in each trial (as in Gazzaley et al., 2005); the horizontal line presented in Fig. 2 remained onscreen in the center throughout the delay.

For each trial, the 'target' was defined as the letter occupying the same position as the subsequent dot (this time .36°×.36°); the other letter was defined as the 'distractor' (2.03°×2.98° for the whole stimulus array). Stimuli were presented in random order. Each trial began with a ready prompt (?). (See time course of sample trial in Fig. 2.) When ready, participants pressed the space bar with their left hand. This was followed by a blank screen (300 ms) and a fixation (+, for 500 ms). Then the prompt letters (24 point Helvetica, .48°×.60°) appeared for 1 s. In Identical, the letters above and below the horizontal line were the same (e.g., S above S; 48 trials, 12 replications for each letter). In PI, targets and distractors were associated with the same response but with different letters (e.g., S above M; 24 trials, 6 replications of each possible combination). In RI, targets and distractors were associated with different responses and different letters (e.g., S above P; 24 trials, 6 replications of four possible combinations). Stimuli in these 96 trials were presented in random order. Care was taken to ensure that participants responded to letters in either the top or bottom position an equal number of times and that the letter positions were counter-balanced (e.g., "S above M" was presented as often as "M above S") within-subject. After the response and 2 s, participants were asked, "How strong was your urge to make a mistake?", which they rated on an 8-point scale, in which 1 signified "almost no urge" and 8 signified "extremely strong urge." The RT trimming procedure from Experiment 1A resulted in the loss of 117 (6.8%) out of 1728 trials. Because of the removal of erroneous trials and RT trimming, the total RT data removed was 138 (8.0%) of 1728 trials. Regarding the subjective ratings, typographical errors and omitted responses resulted in the loss of 27 (1.56%) of 1728 ratings.

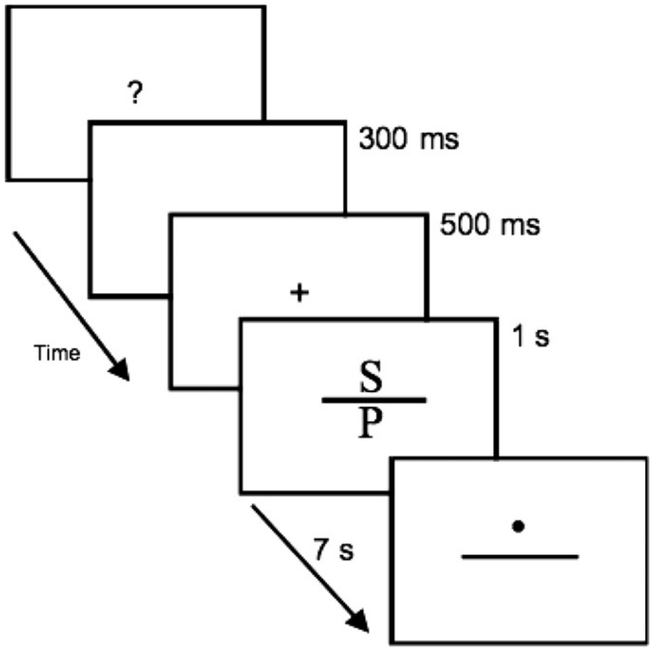

Fig. 2. Time course of stimulus events. Not drawn to scale.

3.3. Results

3.3.1. Error rates

ANOVA revealed that interference condition had a significant effect on error rates, $F(2, 34) = 7.53$, $p = .002$, $ps_{\text{planned comparisons}} < .05$, $ts > 2$; PI led to a lower error rate than Identical ($M_{\text{Identical}} = .011$, $SEM_{\text{Identical}} = .004$; $M_{\text{PI}} = .002$, $SEM_{\text{PI}} = .002$; $M_{\text{RI}} = .036$, $SEM_{\text{RI}} = .011$). This was an unexpected pattern, which remains to be explained. Analysis on arcsine transformations of the data revealed a similar pattern, with condition having a significant effect on error rates, $F(2, 34) = 8.82$, $p = .0008$. In this analysis, the contrast between Identical and RI was marginally nonsignificant, $t(17) = 2.017$, $p = .0598$. The remaining contrasts were significant, $ps < .02$.

3.3.2. Subjective effects

ANOVA revealed that the pattern of results of the urges to err mirrored that of the RT analysis (Table 2), with there being an effect of condition, $F(2, 34) = 15.13$, $p < .0001$ ($\eta_p^2 = .47$), and all the planned contrasts between conditions being significant ($ts > 3.9$, $ps < .01$), except that between PI and Identical, $ts = 1.52$, $p = .147$.

Table 2
Effect of condition on reaction time (ms) and urge to err for Experiment 1B.

	Condition		
Reaction time	Identical	Perceptual interference	Response interference
Mean	521.13	549.92	808.46
SEM	31.42	36.98	66.80
Urge to err			
Mean	1.56	1.74	3.08
SEM	.20	.29	.49

3.3.3. Response times

The mean RT per participant was 595.52 ($SEM = 37.72$). Mean RTs for the three different conditions (Identical, PI, and RI) followed the pattern typically seen in the traditional flanker paradigm (Table 2). ANOVA revealed an effect from interference condition, $F(2, 34) = 42.55$, $p < .0001$ ($\eta_p^2 = .71$). Planned comparisons revealed significant contrasts between all conditions ($ts > 6.6$, $ps < .05$) except between Identical and PI, $t(17) = 1.78$, $p = .09$, although a statistical trend was present. The same pattern of results, including the significant ($ps < .05$) contrasts, is obtained when including trials in which participants made an incorrect response, $F(2, 34) = 41.97$, $p < .0001$ ($\eta_p^2 = .71$).

In summary, in standard analyses, there is always a main effect of condition, and all the contrasts are significant except that between PI and Identical.

3.3.4. Correlation between RTs and urges

An analysis including erroneous trials revealed that, again, RT correlated with urges: The average *r* across subjects was .37, Fisher's *r* to *z*, $p < .05$, which is significant given the number of observations per subject. This correlational trend was also found within condition ($r_{\text{Identical}} = .28$, $r_{\text{PI}} = .17$, and $r_{\text{RI}} = .17$).

3.3.5. Discussion

As predicted, in a task involving action-related representations that were held in WM, we found the same inter-representational dynamics found with externally-generated stimuli. The subjective effects of the RI condition are consistent with the findings from research examining the subjective effects of sustaining incompatible intentions (Morsella, Gray, Krieger, & Bargh, 2009). It seems that a representation that is associated with a response-related process is likely to activate that process to some extent (e.g., as in priming), even when the efference is undesired in the present task. This is consistent with what has been found in previous flanker paradigms (Eriksen & Schultz, 1979). Participants knew that one of the two stimuli would serve as the target, so it is not surprising that priming for both responses might have occurred during the delay interval and that, during action selection in response to the target, having sustained two representations in mind yielded RI and PI effects. As mentioned above, one limitation of these data is that the RI condition involves a choice-RT task whereas the PI condition could perhaps be treated by participants as if it were a simple RT task. Nevertheless, the same pattern of results from Experiment 1A is encountered in a more challenging context, suggesting that our paradigm is robust.

4. Experiment 2

4.1. Replication without flanking distractors

As initial behavioral and subjective effects from our paradigm, the results from the delayed action task in Experiment 1 demand replication. In addition, several questions remain unanswered. In Experiment 1, throughout the course of a given RI or PI trial, information about targets appeared only once, at the beginning of the trial. However, at the end of the trial, multiple cues (two in number) were intended to activate (or ‘prime’) representations that were different from that actively held in WM by the participant. Do the behavioral and subjective RI effects from Experiment 1A require that, within a trial, mismatching distractors be presented more often, thereby leading to more priming than that caused by the single presentation of the target? Would similar effects be obtained if distractors are presented as often as targets, that is, only once? Experiment 2 addressed this question and also provided a replication for the initial behavioral and subjective findings from Experiment 1A.

4.2. Method

4.2.1. Participants

SFSU undergraduates ($n = 32$) participated for class credit.

4.2.2. Procedure

After a training session identical to that of Experiment 1, participants were told that they should continue to respond to the letter (24 point Helvetica, .48° × .60°) in the center of the screen (the target) but to delay responding until they see a subsequent letter (the distractor), which always appeared after 7 s. Participants were instructed to disregard the characteristics of the distractor and emit only the response associated with the target. In the Identical condition, targets were followed by distractors that were identical to the target (e.g., S followed by S; 48 trials, 12 replications for each letter). In the PI condition, targets and distractors were associated with the same response but with different letters (e.g., S followed by M; 24 trials, 6 replications of each possible combination). In the RI condition, targets and distractors were associated with different responses and different letters (e.g., S followed by P; 24 trials, 6 replications of four possible combinations). Stimuli in these 96 trials were presented in random order. Each trial began with a ready prompt (?). When ready, participants pressed the space bar with their left hand. The target, preceded by a blank screen (300 ms) and a fixation cross (500 ms), appeared for 1 s. After the response and 2 s, participants were asked the same question presented in Experiment 1A. One participant ended the session early, completing 64.6% of the trials. Of the remaining data, the RT trimming procedures of Experiment 1A resulted in the loss of 128 (4.2%) out of 3038 trials. Because of the removal of erroneous trials and RT trimming, the total RT data removed was 337 (11.1%) of 3038 trials. Regarding the subjective ratings, typographical errors and omitted responses resulted in the loss of 33 (1.09%) of 3308 ratings.

4.3. Results

4.3.1. Error rates

Errors occurred on 253 (8.33%) of 3038 trials. Condition had a significant effect on error rates, $F(2, 62) = 6.326$, $p < .01$, but planned comparisons revealed that the only significant differences ($ps < .05$) were between RI ($M = .19$, $SEM = .052$) and the other two conditions ($M_{\text{PI}} = .066$, $SEM = .029$; $M_{\text{Identical}} = .051$, $SEM = .025$). Concerning errors, Identical and PI were statistically comparable. Analysis on arcsine transformations of the data revealed a similar pattern of results, with condition having a significant effect on error rates, $F(2, 62) = 9.232$, $p = .0003$, and the significant contrasts being those involving the RI condition.

4.3.2. Subjective effects

ANOVA revealed an effect of interference condition, $F(2, 62) = 10.06$, $p = .0002$ ($\eta_p^2 = .25$), and all the planned contrasts between conditions being significant ($ts > 2.4$, $ps < .05$): Identical ($M = 1.89$, $SEM = .26$), PI ($M = 2.08$, $SEM = .27$), and RI ($M = 2.34$, $SEM = .27$).

4.3.3. Response times

The mean RT per participant was 628.58 ($SEM = 38.48$). In line with our hypothesis, the mean RTs for the three different conditions (Identical, PI, and RI) followed the pattern typically seen in the traditional flanker paradigm: Identical ($M = 599.94$, $SEM = 37.74$), PI ($M = 629.88$, $SEM = 41.28$), and RI ($M = 651.57$, $SEM = 43.34$), $F(2, 60) = 4.28$, $p = .018$ ($\eta_p^2 = .12$), except that, in the planned contrast analysis, one contrast is not significant—that between RI and PI, $t(30) = 1.03$, $p = .31$. That this contrast is nonsignificant may be due in part to unbalanced loss of RT data, stemming from excluding RTs associated with incorrect responses. Consistent with this notion, first, all contrasts are significant ($ts > 2.3$, $ps < .03$) in an analysis that included RT data from trials in which participants erred, $F(2, 62) = 12.60$, $p < .0001$ ($\eta_p^2 = .29$), and, second, the contrast between RI and PI is significant ($t > 3$, $p < .01$) in an analysis that excluded participants who, for any condition, had more than 20% data loss (from data trimming and the exclusion of erroneous trials). Last, the contrast between RI and PI is significant ($t = 3.19$, $p < .01$) in an analysis including only the data from participants ($n = 16$) who had low percentages (<5%) of data loss.

4.3.4. Correlations between RT and urges

An analysis including erroneous trials revealed that RT correlated with urges: The average r across subjects was .25, Fisher's r to z, $p < .05$, which is significant given the number of observations per subject. The correlational trend was also found within condition ($r_{\text{Identical}} = .26$, $r_{\text{PI}} = .28$, and $r_{\text{RI}} = .30$).

4.3.5. Discussion

Again, as in Experiments 1A and 1B, traditional perceptual and response interference, including their behavioral and subjective aspects, were obtained in a delayed action task. In addition, the present findings rule out that the effects of Experiments 1A and 1B were due to disproportionate priming from distractors.

5. General Discussion

In different variants of our delayed action task, we found the same pattern of both subjective and behavioral effects, which is the same pattern that is found with the three conditions of the classic flanker task: Identical, Perceptual Interference, and Response Interference (Eriksen & Schultz, 1979; Morsella, Wilson, et al., 2009). To assess the nature of interference during WM-based action control, we used a variant of the flanker task because this paradigm is the best suited for distinguishing the consequences of different kinds of interference conditions (Eriksen, 1995). In addition, unlike in interference paradigms in which word stimuli (Stroop, 1935) or arrow-like stimuli (e.g., Eriksen & Eriksen, 1974; Hommel, 1996) are used as distractors, in our version of the flanker paradigm, distractors exerted their influence in virtue only of learning that occurred in the laboratory. Prior learning or knowledge played a minimal role in the interference effects. Because the task instructions for Experiment 2 are so simple, it may be feasible to use this task with patients suffering from disorders that involve action selection and action control.

In Experiments 1A and 2, systematic interference effects were obtained under conditions of response certainty (a conceptual replication of Hommel, 1996). Again, to respond accurately, participants did not need to identify the identity of distractors. For all experiments, our response preparation interval was longer than that used previously, by at least 5 s (cf., Hommel, 1996). It is notable that systematic interference effects still arose under these conditions. In addition, interference effects were obtained even though one of the action-related representations was activated, not by stimuli in the external world, but by mechanisms in WM. A similar pattern of results was obtained in Experiment 1B, involving a paradigm that included increased response uncertainty. Because of an inherent confound, these data cannot stand by themselves (as explained above). Nevertheless, the data are useful when interpreted along with the findings from Experiments 1A and 2. At the very least, the data from Experiment 1B corroborate that the interference phenomena from Experiments 1A and 2 are robust and can arise even under more challenging circumstances.

The findings from Experiments 1A and 2 seem to counter the prediction based on the ballistic hypothesis (Berlucchi et al., 1977; Lashley, 1951), which predicts that, with a response preparation spanning 7 s and response certainty, any distractor-based interference should be eliminated. Instead, the findings are directly in line with previous findings (e.g., Hommel, 1996). Previous studies have shown interference effects under similar conditions. However, as mentioned above, what is novel about our approach is that our paradigm included the contrasts involving Identical, PI, and RI. In addition, our project had as its central focus the subjective aspects of responding.

5.1. Limitations

The limitations of the present studies naturally include the limitations of the flanker task. To take one example, representations giving rise to RI must include some perceptual interference. This may render the RI condition more complicated than the PI condition; this added difficulty of the RI condition could perhaps lead to the kinds of effects reported above. Unfortunately, a flanker-like paradigm that can induce RI without also invoking perceptual interference has never been developed (Morsella, Wilson, et al., 2009). This could be instantiated by having targets and distractors perceptually identical but somehow cue different responses, a scenario that is difficult to fathom. Nevertheless, as mentioned above, there are empirical bases and theoretical reasons (e.g., Morsella, 2005) to believe that RI is qualitatively distinct from perceptual interference. To reiterate one reason, in a neuroimaging study, van Veen et al. (2001) demonstrated that, although both RI and PI are associated with differences in performance, the former is the condition that activates the ACC.

Regarding the limitations of Experiment 1B, it could be argued that the RI effect simply reflects the fact that, in this task, the RI condition involves choice RT, and the PI condition involves only simple RT, as discussed above. Of course, one could also argue that it is precisely because of the kind of response selection occurring in our RI condition that choice RT happens to be longer than simple RT. Another limitation of this experiment, which is shared by the other two experiments, is that it remains to be determined whether the PI condition leads to actual interference or whether responding in this condition reflects a true measurement of what could be considered ‘baseline’ speed. From this standpoint, responding in the Identical condition may reflect, not a true baseline condition, but response facilitation. This limitation is apparent in many flanker variants (cf., Morsella, Wilson, et al., 2009). Another limitation in our experiments involves the issue of recoding of the $S \rightarrow R$ contingencies in terms of motor responses. When presented with the prompt S and M, perhaps participants simply recode the memorandum as “respond with index finger” instead of holding in mind two $S \rightarrow R$ contingencies. Participants may use different strategies for performing the task, and it is likely that this re-mapping may have occurred to some extent, at least for some trials and for some subjects. However, knowledge of this possibility raises questions regarding why contrasts between PI and Identical still arose systematically and in several cases, even though the response recoding algorithm for PI and Identical would be of comparable difficulty. This issue warrants further investigation.

At this stage, studying the subjective aspects of these action-related processes is best explored by having subjects self-report about their cognitive processing. In such an arrangement, it has been found that, though far from perfect, ‘urges to err’ are a practical and reliable way to assess the perturbations in consciousness due to different forms of interference (Morsella, Berger, & Krieger, 2011; Morsella, Gray, Krieger, & Bargh, 2009; Morsella, Wilson, et al., 2009).[3] Because of the limitations inherent in all introspection paradigms, we cannot rule out that judgments were based on self-observations involving RT performance or on other strategies, such as basing judgments on folk beliefs regarding how one should comport oneself in an experiment about interference. Perhaps participants based their ratings on heuristics such as, "if the targets and distractors are associated with different actions, then I will always report 6 as the rating." Although this cannot be fully ruled out by the present studies, this alternative seems unlikely given that participants' ratings tended to vary across trials within each condition. For instance, for the RI condition, the first four ratings from a participant selected at random from Experiment 1A were *3*, *2*, *2*, and *1*. Of course, it may well be that participants were using a more sophisticated and nuanced heuristic when engendering the current data (Morsella, Wilson, et al., 2009). At this stage of understanding, we believe our subjective measure provides a portal through which to begin to explore the conscious aspects of different kinds of inter-representational dynamics. Future investigations on action production and WM are necessary to qualify the kinds of conclusions that can be drawn from this present, initial project.

5.2. Implications

Despite the limitations inherent in collecting self-report data, these data are valuable in light of current theorizing regarding the difference between implicit and explicit processing and the proposed systems that may be involved for each kind of processing (Etkin et al., 2010; Goodale & Milner, 2004; Gyurak et al., 2011; Schacter, 1996). That RI led to the strongest subjective effects adds to a growing literature supporting the view that consciousness is intimately related to response selection (see review of evidence in Morsella, Berger, & Krieger, 2011) and complements findings regarding the 'conscious impenetrability' of smooth muscle conflicts (Morsella, Gray, Krieger, & Bargh, 2009), intersensory conflicts, and other conflicts occurring among perceptual representations (Morsella, 2005; Sanders, 1983). One theoretical framework (Morsella, 2005) proposes that, in the nervous system, there are three distinct kinds of integration or 'binding' (Morsella & Bargh, 2011). Perceptual binding (or *afference binding*) is the binding of perceptual processes and representations, which can occur unconsciously. This form of binding occurs in feature binding (e.g., the binding of shape to color; Zeki & Bartels, 1999) and intersensory binding, in which disparate senses integrate information across the perceptual field (e.g., visual and auditory inputs regarding the source of a sound interact unconsciously). (See additional evidence for unconscious afference binding in Zmigrod & Hommel, 2011.) The second form of binding (*efference binding*) links perceptual processing to action/motor production processing (Haggard, Aschersleben, Gehrke, & Prinz, 2002). This kind of stimulus–response ($S \rightarrow R$) binding allows for automatic button presses in response to a cue. Research has shown that efference binding can happen unconsciously, as during reflexes (e.g., reflexive pain withdrawal) and when subjects are able to select the correct motor response (one of two button presses) when confronted with a subliminal cue (Fehrer & Biederman, 1962; Fehrer & Raab, 1962; Hallett, 2007; Taylor & McCloskey, 1990, 1996). The third form of binding, *efference–efference binding*, occurs when two streams of efference binding are trying to influence skeletomotor action simultaneously (Morsella & Bargh, 2011), as when one holds one's breath or suppresses color naming in the classic Stroop color-naming task. The RI condition of the present study includes efference–efference binding. According to the theoretical development (Morsella, 2005), it is efference–efference binding that requires conscious processing (see evidence in Morsella, Berger, & Krieger, 2011). This approach explains why holding one's breath—or performing the Stroop incongruent condition or the RI condition of the present studies—leads to changes in consciousness (e.g., "urges").

More generally, these basic findings are consistent with research showing that representations preserve the sensorimotor properties (including motor programs) of the states associated with the acquisition of the relevant information (Barsalou, 2003; Cappelletti, Fregni, Shapiro, Pascual-Leone, & Caramazza, 2008; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Pulvermuller, 2005), and with theoretical approaches proposing that mental representations and internalized actions (e.g., subvocalization) retain the psychological properties of overt action (Morsella, Wilson, et al., 2009; Vygotsky, 1962; Zwaan, 2008). (See criticisms against such 'embodied' approaches in Mahon & Caramazza, 2008; see evidence addressing these criticisms in Niedenthal, Winkielman, Mondillon, & Vermeulen, 2009; Pitcher, Garrido, Walsh, & Duchaine, 2008.) In addition, these findings provide additional information about the nature of cognitive control in working memory (Gazzaley & D'Esposito, 2007) and action production, an under-explored area of research (Rosenbaum, 2005).

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[3] It is important to note that urges to err can be based on different aspects of responding in the task. There is evidence that participants sometimes base their judgments on superficial stimulus dimensions such as the particular letters that were presented on a given trial (Morsella, Wilson, et al., 2009). However, it has been proposed that a large part of the difference between RI and PI stems from the activation of incompatible action plans in the former, a proposal for which there is evidence (cf., Morsella, Berger, & Krieger, 2011). The measure of a subject's urge to err is not a perfect measure of the subjective aspects associated with processing, but it seems to be the most reliable and practical measure. It is important to note that, in such introspection-based studies, due to the inherent limitations of language and communication, the experimenter is limited with respect to what can be learned from the subject's self-report. For instance, because the average naïve subject will not understand what the experimenter means by 'subjective experience' or 'subjective modulation,' it is only through commonly understood concepts and terms such as 'urge to make a mistake' that an experimenter can infer any systematic changes in the subject's subjective experience. It is worth keeping in mind that these self-reports are only an index associated with what the experimenter is really concerned about—changes in the conscious field from, say, the activation of incompatible skeletomotor intentions.

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