THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY
2010, 63 (4), 653–665

Psychology Press
Taylor & Francis Group

Auditory negative priming endures response modality change; prime response retrieval does not

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Two auditory identification experiments were run to test a specific hypothesis about the prime response retrieval mechanism of negative priming. This mechanism operates in ignored repetition trials where the prime distractor repeats as the probe target and leads to an increase of probe errors with the former prime response (Mayr & Buchner, 2006). Participants identified target sounds while ignoring distractor sounds. They changed from verbal (prime) to manual (probe) responding. Concomitant manual prime responses were prevented right from the start in Experiment 1 ($N = 72$) but not in Experiment 2 ($N = 49$). Experiment 1 revealed a negative priming effect in response speed but no prime response retrieval effect—that is, there was no increase in prime errors to the probes of ignored repetition trials. This pattern of results implies that retrieval of prime responses takes place at the level of motor responses (e.g., retrieval of the motor programme of a right index finger key press) but not at the level of task-specific response codes (e.g., retrieval of the "piano" response alternative). Experiment 2 replicated the negative priming effect across response modalities and helped to clarify the importance of prime response processes for finding a negative priming effect in overall error rates.

Keywords: Negative priming; Prime response retrieval; Episodic retrieval; Response modality change; Auditory selective attention.

The negative priming effect—a slowed-down and more error-prone responding to a stimulus that had to be ignored previously—is a robust phenomenon (see May, Kane, & Hasher, 1995; Mayr & Buchner, 2007; Tipper, 2001). Of the different explanatory accounts that have been proposed, only the distractor inhibition model (Houghton & Tipper, 1994; Tipper, 1985, 2001; Tipper & Cranston, 1985) and the episodic retrieval model (Neill & Valdes, 1992; Neill, Valdes, Terry, & Gorfein, 1992) seem to have outlived theoretical debates and experimental tests (Mayr & Buchner, 2007).

A variant of the episodic retrieval model, the prime response retrieval model, recently received experimental support (Mayr & Buchner, 2006; Rothermund, Wentura, & De Houwer, 2005). This variant and the original episodic retrieval

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We thank Katharina Drusch for her assistance with data collection. The research reported in this article was supported by a grant from the Deutsche Forschungsgemeinschaft (Ma 2610/2–1).

http://www.psypress.com/qjep
DOI:10.1080/17470210903067643

model (Neill & Valdes, 1992) share the core assumption that negative priming is the result of retrieving parts of the prime episode when the probe presentation contains an appropriate retrieval cue. It is assumed that the previous distractor that is repeated as the probe target in ignored repetition trials functions as such a retrieval cue. Retrieval of the prime episode cannot occur in control trials in which all prime and probe stimuli are different. The two episodic retrieval model variants differ in what they assume to be the retrieved prime episode information. The original model assumes that retrieving "do-not-respond" information tied to the prime distractor is critical because it conflicts with the requirement to respond to the (similar or identical) probe target. Resolving this conflict takes time—hence the negative priming effect. The prime response retrieval variant postulates that the response associated with the prime target is retrieved in ignored repetition trials. When retrieved, this response is usually inappropriate for probe responding and leads to a time-consuming response conflict. Both retrieval mechanisms may operate simultaneously.

The prime response variant uniquely predicts that incorrect repetitions of prime responses to probe targets should be overrepresented in the errors on ignored repetition trials compared to control trials. Mayr and Buchner (2006) confirmed this prediction in a four-alternative identification task in which every stimulus required a unique response. The original episodic retrieval model cannot predict this data pattern because erroneous retrieval of the prime response is not a model-specific process. Similarly, an inhibition model assuming reduced activation of the former prime distractor representation (Houghton & Tipper, 1994; Tipper, 1985, 2001) or suppression of its translation into a response code (Tipper & Cranston, 1985) cannot account for an overrepresentation of prime response errors.

Rothermund et al. (2005) proposed a model very similar to the prime response retrieval model and provided supporting evidence in a series of task-switching experiments. For example, participants categorized the colour of a prime word as yellow or green with a left or right key response. In the probe, a word had to be categorized as adjective or noun with the same keys. When the response had to be repeated from prime to probe, repeated words received faster responses, but when the alternative response had to be given, word repetition slowed down responding relative to probe trials with new words. This data pattern is compatible with the conclusion that the prime response was retrieved and was response compatible in the first case but response incompatible in the second.

The findings of Mayr and Buchner (2006) and of Rothermund et al. (2005) support the assumption that a prime response retrieval mechanism is involved in the negative priming effect. Mayr, Buchner, and Dentale (2009) went on to show that the increase of prime response errors crucially depends on the execution of the prime response. In three go/no-go experiments participants responded in primes with a go signal, but refrained from responding when a no-go signal was presented. An increase in prime response errors in ignored repetition relative to control trials was found in go trials (i.e., after prime response execution), but not in no-go trials (i.e., without prime response execution).

The data of Mayr et al. (2009) point at the necessity of response execution for prime response retrieval to occur, but the type of information that is retrieved is still unclear. Specifically, prime and probe responses could be represented in two different ways. First, retrieved response representations may comprise the motor programme of the response that was executed (such as the movement of the right index finger pressing the key). Second, retrieved response representations may be more abstract, consisting of task-specific response categories (such as the "piano" response alternative, independent of response mode). Prime responses in either type of representation could result in prime response retrieval errors. It is thus open whether prime response retrieval is tied to retrieval of a *specific* motor response or of the prime response alternative in terms of a task-specific representational format. An experimental test of these two alternatives can be achieved by changing the response mode between prime and probe, such as from a spoken prime response to a manual probe response. This was implemented in the experiments presented here. As a consequence, prime and probe responses no longer shared the same motor programme but they still shared the representation in terms of the task-specific response format (e.g., the "piano" response alternative). If the prime response retrieval effect survived the response mode change, then this would imply that the effect is based on retrieval of responses in task-specific representational format. Alternatively, if prime response retrieval vanished after response mode changes, then this allows for the conclusion that the effect is limited to retrieval of motor responses.

Tipper, MacQueen, and Brehaut (1988) demonstrated in a visual identification task that negative priming can be found in spite of response mode changes (from verbal responding to key presses, or vice versa, see also Rothermund et al., 2005). This was interpreted as evidence against a response locus of negative priming, an interpretation that is obviously relevant for the prime response mechanism. We thought it important to replicate the finding of negative priming across response modes in the present auditory Experiment 1. Given that visual and auditory negative priming share essential determinants (Mayr & Buchner, 2007), we expected auditory negative priming to occur across response modalities.

EXPERIMENT 1

Method

Participants

Participants were 72 adults (mostly students, 52 female). They ranged in age from 19 to 38 years ($M = 25.11$, $SD = 4.16$). Data of 3 additional participants who did not pass one of the training phases were discarded. All participants were tested individually.

Materials

The stimuli were four digitized sounds (frog, piano, drum, bell). Each sound was 300 ms long. Participants heard the sounds over earphones that were plugged into an Apple iMac.

Each experimental trial consisted of a prime and a probe display. For both types of displays, a 20-ms metronome click indicated the ear at which the to-be-attended sound would be presented. A simultaneously presented distractor appeared at the other ear. The attended ear in the prime display was randomly assigned; the attended probe sound was presented to the opposite ear. In the prime, participants named the object associated with the attended sound. In the probe, participants pressed the response key assigned to the attended sound. The response keys were sagittally aligned on a response box. They were labelled with the colour of the object that was associated with the respective sound in the instructions (green for frog, black for piano, blue for drum, red for bell).

Ignored repetition trials were constructed by randomly selecting three of the four stimuli as prime and probe sounds with the restriction that the ignored prime had to be identical to the attended probe (Table 1). Next, parallel control trials were constructed by replacing the ignored prime with the remaining stimulus (*piano* replaced by *bell* in the example in Table 1). Within these two types of trials the ignored prime stimulus would have been the attended probe stimulus on 50% of the trials, and the prime target would never have been equal to the probe target. Therefore, attended repetition trials were constructed by generating all combinations of three out of the four sounds with the restriction that the attended prime and probe had to be identical. Attended repetition control trials were constructed by replacing, in the attended repetition trials, the attended prime with the remaining stimulus.

Note that an ignored repetition trial always shared its control trial with an attended repetition control trial (see Table 1 for an example). Had we used the entire set of trials that can be generated by the algorithm just described, then every control trial would have occurred twice, possibly resulting in an unwanted response speed-up at the second presentation of each control trial (which would artificially increase the negative priming effect).

Table 1. *Examples of stimulus configurations and required responses*

	Ignored repetition		*Control*		*Attended repetition*		*Attended repetition control*	
	Attended ear	*Ignored ear*	*Attended ear*	*Ignored ear*	*Attended ear*	*Ignored ear*	*Attended ear*	*Ignored ear*
Prime	Frog *"frog"*	Piano	Frog *"frog"*	Bell	Piano *"piano"*	Bell	Frog *"frog"*	Bell
Probe	Piano *piano key*	Drum	Piano *piano key*	Drum	Piano *piano key*	Drum	Piano *piano key*	Drum

Note: Required responses in italics. Verbal prime responses are indicated by quotation marks.

In order to avoid this confound, ignored and attended repetition trials were systematically assigned to Set 1 or Set 2 with three restrictions: First, identical control trials had to belong to different sets. Second, within each trial type, the frequencies of the different sounds had to be identical. Third, the frequencies of the combinations of attended and ignored sounds within the prime and within the probe pairs had to be equal for the different trial types. Participants were randomly assigned to the sets.

Each set comprised 48 unique trials, including 12 trials of each of the four trials types. A set was presented three times, resulting in 144 experimental trials presented in a random sequence.

Procedure

First, participants were given opportunity to adjust the loudness of the sounds to a comfortable level. On average the loudness was set to 64 dB(A). Next, participants learned the prime task of verbal responding. It seemed conceivable that participants might execute key presses while verbalizing the prime target given that the task required perpetual switching between verbal prime and manual probe responding. This behaviour would undermine our hypothesis test. If participants performed manual responses while verbalizing, a possible prime response retrieval effect could be due to retrieval of these manual motor responses (for more details, see the Discussion section and Experiment 2). Therefore, manual responding in the primes had to be prevented right from the start. As an important measure to prevent simultaneous manual responding, participants had to press down all response keys. A photo depicting the response fingers pressing down the four keys was used to prompt participants to press down all response keys as shown. When all keys were pressed down, a click indicated the randomly selected ear. Then, a randomly selected target sound was presented at that ear. A to-be-ignored distractor was presented simultaneously to the other ear. Participants reacted to the target sound by naming the associated object. Subsequently, they released the response keys. Participants were given feedback about the correctness of each reaction. To this end, the experimenter immediately coded the response, using a second monitor outside the participant's range of vision behind a movable wall. Participants entered the next training phase if 8 or more of the preceding 10 responses had been correct.

In the second training phase, participants learned the probe task. They reacted to the target sound by quickly pressing the corresponding key. They were given feedback about the correctness of each reaction. Participants entered the next training phase if 15 or more of the preceding 20 responses had been correct. In the third training phase entire prime–probe trials were presented, and participants had to respond verbally to the prime and manually to the probe. They were given feedback about the correctness of both responses. Participants entered the experiment proper when their responses were correct in 6 of the preceding 10 trials. Participants who did not reach a training criterion within 40 trials (prime training phase, probe training phase) or within 20 trials (prime–probe training phase) were given the choice to quit or to start anew. A total of 7 participants successfully repeated the training phases.

Each of the 144 experimental trials began with the presentation of the visual signal prompting participants to press down the response keys. When all keys were pressed, the click was presented to the to-be-attended ear. After a 500-ms click–target interval, the prime sounds were presented. Participants were to respond verbally within 2,000 ms after prime onset. After this response window, the visual signal vanished. In the following 2,000-ms prime–probe interval the monitor stayed blank, providing enough time for the experimenter to code the prime response and for the participant to release the response keys before probe stimulus presentation. The probe click was followed by a 500-ms click–target interval, after which the probe sounds were presented. Participants had to respond manually within 2,000 ms after probe onset. After each prime–probe trial participants were given audio-visual feedback about the correctness of their responses. A 2,000-ms intertrial interval followed before the visual signal of the next trial was presented. After every 12th trial, participants received a summary feedback about their average reaction times and percentage of errors. After the final trial, all participants were informed about the purpose of the experiment. The experiment took about 45 min.

Design

The experimental design comprised the trial type within-subject independent variable (ignored repetition vs. control). The dependent variables were the probe error frequency, accumulated across participants, as well as participants' average reaction times and overall error rates.

The a priori power analysis was based on the prime response retrieval effect—that is, the difference between the prime response retrieval parameters prr_{IR} and prr_{C} for the ignored repetition and control condition, respectively (see Results section). The sample effect size of this difference was $w = 0.065$ in an auditory identification task reported by Mayr and Buchner (2006). This task was similar to the one used here, except that there was no prime-to-probe response mode change. Given that the change in response modes can be expected to reduce the effect, and also considering that sample effect sizes tend to overestimate population effect sizes, it seemed reasonable to base our power analysis on a population effect size of $w = 0.05$ for the prime response retrieval effect. We expected that each participant would contribute about 66 probe responses that followed a correct prime response and thus could be evaluated (i.e., about 90% of the 36 possible probe responses in the ignored repetition and control conditions). Under these conditions and assuming desired levels of $\alpha = \beta = .05$, data had to be collected from a sample of 79 participants (Faul, Erdfelder, Lang, & Buchner, 2007). We were able to collect data from 72 participants (overall $N = 4{,}930$), so that the power was slightly smaller than what we had planned for ($1 - \beta = .94$).

Results

Probe reaction times were evaluated only for trials with correct primes and probes. Probe errors were evaluated only if they followed a correct prime.

The means of participants' average probe reactions (Figure 1, left side) were significantly slower in ignored repetition than in control trials, $t(71) = 3.88$, $p < .01$, $d_z = 0.46$. The number of errors did not differ between ignored repetition and control trials, $t(71) = 1.13$, $p = .26$, $d_z = 0.13$ (Figure 2, left side).

In a next step, we analysed the error frequency data displayed in Table 2 using the multinomial model introduced by Mayr and Buchner (2006, see Figure 3). The model represents the processing stages presumably involved in generating a probe response in a four-alternative forced-choice (4AFC) task for both the ignored repetition and the control condition. Participants correctly identify and respond to the probe target with probability *ci*. Errors ($1 - ci$) might have different causes. Participants might experience a *probe stimulus confusion* in that they confuse target and distractor and respond with the probe distractor with conditional probability *psc*. If probe stimulus

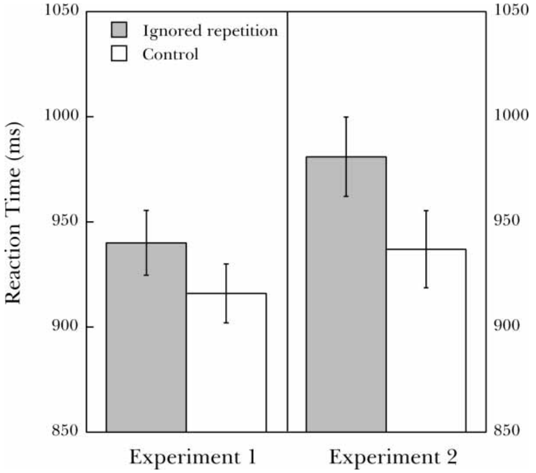

Figure 1. *Mean reaction times in Experiment 1 (left side) and Experiment 2 (right side) as a function of trial type. The error bars depict the standard errors of the means.*

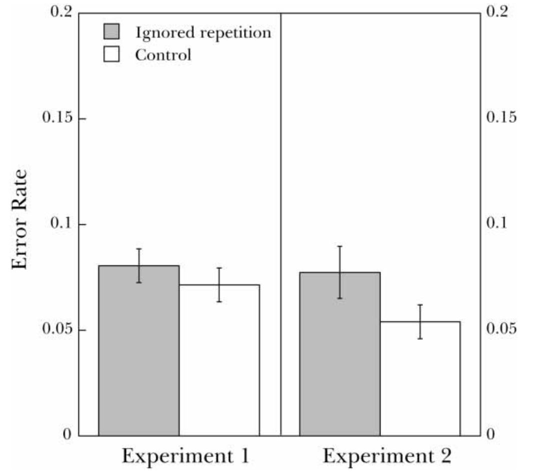

Figure 2. *Error rates in Experiment 1 (left side) and Experiment 2 (right side) as a function of trial type. The error bars depict the standard errors of the means.*

confusion does not dominate responding ($1 - psc$), then, with probability *prr*, *prime response retrieval* may occur and lead to incorrect prime responses. If prime response retrieval occurred in the present experiment despite the response mode change, then the probability of retrieving a prime response in the ignored repetition condition, prr_{IR}, is expected to be larger than prr_C, the same probability in the control condition. Thus, if $prr_{IR} > prr_C$ and if, in addition, the goodness-of-fit test of the restricted model assuming $prr_{IR} = prr_C$ leads to a significant misfit, then this is evidence in favour of the assumption that prime response retrieval occurs and contributes to the negative priming effect.

The unrestricted multinomial model as displayed in Figure 3 fitted the present frequency data perfectly. The prime response retrieval parameters prr_{IR} and prr_C are illustrated in Figure 4 (left side). We tested the goodness-of-fit of the model with the restriction that $prr_{IR} = prr_C$. The restricted model fitted the data, $G^2(1) = 0.14$, $p = .71$,[1] and, thus, could not be rejected.

Discussion

The data of Experiment 1 revealed an auditory negative priming effect that endured a change in response mode between prime and probe, at least in reaction times. There was, however, no negative priming effect in the overall error data of Experiment 1. This finding stands in clear contrast to the overall error effects that we usually find in similar auditory negative priming experiments without a response mode change (Mayr & Buchner, 2006, Experiments 2 and 3; Mayr et al., 2009). It is also at odds with findings in the visual modality (Rothermund et al., 2005; Tipper et al., 1988; see further below).

The present data further revealed that the prime response retrieval effect is absent when the task requires a change in response mode from verbal to manual. Participants responded equally (in)frequently with the former prime response in ignored repetition and control trials. The combined pattern of results—absence of negative priming in overall errors and, at the same time,

[1] The log-likelihood goodness-of-fit statistic G^2 is asymptotically χ^2-distributed with the degrees of freedom indicated in parentheses (see Hu & Batchelder, 1994, for details). The goodness-of-fit test was conducted using the AppleTree program (see Rothkegel, 1999).

Table 2. *Accumulated absolute frequencies of correct probe responses and of the different types of probe errors for the ignored repetition condition and the control condition in Experiment 1 and Experiment 2*

	Experiment 1		*Experiment 2*	
	Ignored repetition	*Control*	*Ignored repetition*	*Control*
Correct probe target responses	2,317	2,327	1,549	1,608
Incorrect probe distractor responses	88 (57.9)	84 (62.7)	70 (71.4)	51 (78.5)
Incorrect prime target responses	31 (20.4)	26 (19.4)	15 (15.3)	6 (9.2)
Other incorrect responses[a]	33 (21.7)	24 (17.9)	13 (13.3)	8 (12.3)

Note: Percentage of all errors in parentheses.
[a]Ignored repetition trials: incorrect responses using the key that was assigned to the nonpresented stimulus. Control trials: incorrect prime distractor responses.

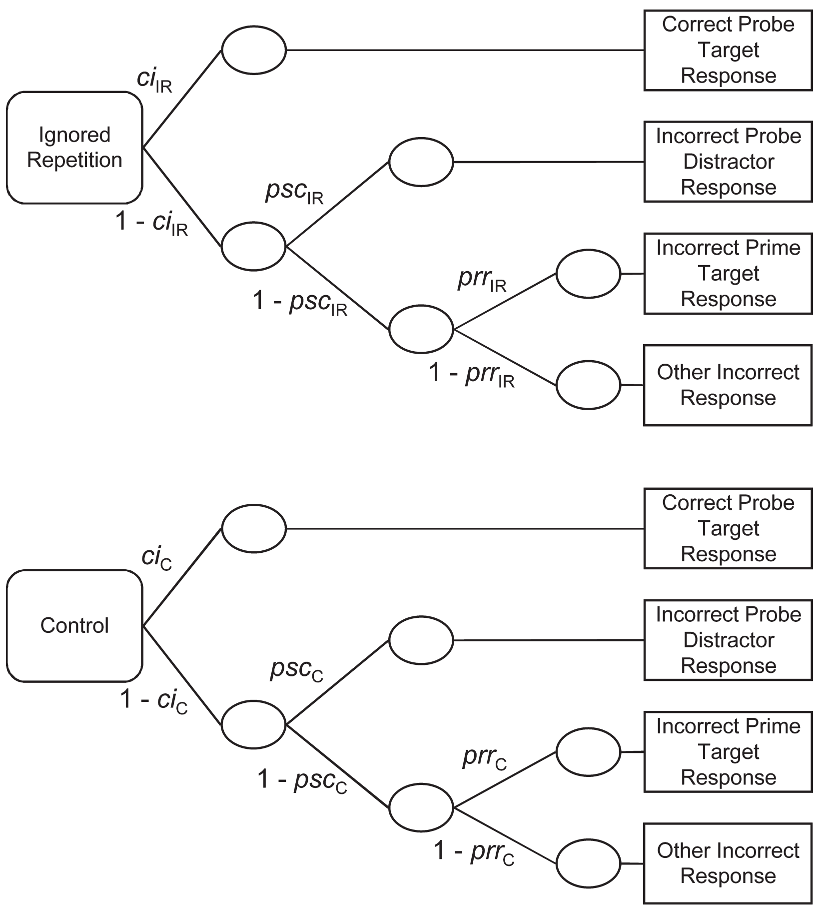

Figure 3. *Multinomial processing tree model ("prime response retrieval model") for analysing the probe reactions in the trial type condition "ignored repetition" (above) and "control" (below). For details see text.*

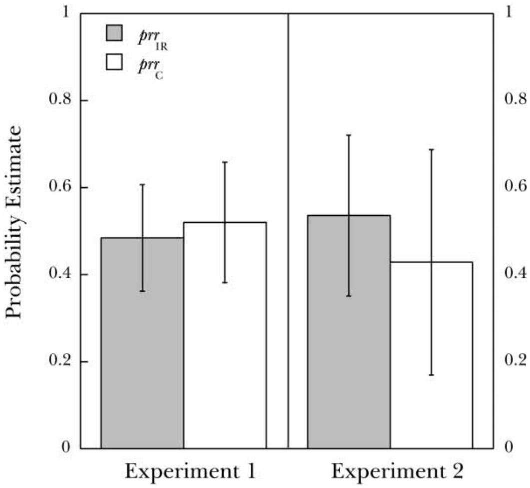

Figure 4. *Probability estimates for the model parameters representing the probability of prime response retrieval as a function of trial type for Experiment 1 (left side) and Experiment 2 (right side). The error bars depict the 0.95 confidence intervals.*

absence of the prime response retrieval effect—suggests that the negative priming effect in overall errors is primarily, if not exclusively, due to the prime response retrieval mechanism. If the mechanism does not operate—for example, after response mode changes as in the present experiment—then the negative priming effect in overall errors vanishes. In contrast, negative priming in response speed does not seem to be exclusively influenced by prime response retrieval processes. This component of the effect may thus be mainly or additionally due to mechanisms other than prime response retrieval, such as nonresponse retrieval (Neill & Valdes, 1992) or inhibitory processes (Houghton & Tipper, 1994; Tipper, 1985, 2001) or both.

The absence of an overall error rate effect in Experiment 1 conflicts with the data reported by Tipper et al. (1988) as well as by Rothermund et al. (2005). In contrast to our results, in their experiments negative priming in overall errors was found across response mode changes. This discrepancy is most likely due to the fact that concurrent probe response activation at the time of the prime was possible in their experiments, whereas we prevented concurrent probe response activation entirely by prompting participants to press down all response keys during the prime.

Tipper et al. (1988) reported a (nonsignificant) negative priming effect in the overall error rates ($p < .087$) that did not interact with the response mode change variable. However, the negative priming effect in their error data *was* descriptively larger in the groups without response mode change (0.6%) than in the groups with a response mode change (0.3%). It seems possible that the interaction analysis suffered from insufficient statistical power. Because Tipper et al. did not take any measures to prevent additional prime response executions in the alternative response mode (e.g., key presses when verbal responses were required), it is also conceivable that their participants prepared and started to execute more or less rudimentary prime responses in the alternative response mode in a certain number of trials. Most of the times, full execution of these prime responses was successfully inhibited, otherwise prime error rates should have been larger. During the probes of ignored repetition trials, however, the (rudimentary) prime responses or the associated response inhibition processes or both may have been retrieved, thereby interfering with correct probe responding. This would then increase an otherwise nonexisting or reduced negative priming effect in the response mode change conditions.

Rothermund et al. (2005) reported evidence for prime response retrieval. Of specific interest here is their Experiment 2 in which prime and probe responses were verbal and manual, respectively. The authors' rationale was similar to ours in that they wanted to test whether response retrieval occurred at the level of "categorical response information" or at the level of "specific motor routines" (p. 486). As in their Experiment 1, Rothermund et al. found evidence for prime response retrieval in spite of a response mode change. Specifically, they found positive priming when primes and probes required the same response alternative (e.g., verbal response "left" in the prime, manual left response in the probe) whereas negative priming was found when different response alternatives were required in prime and probe (e.g., verbal response "right", manual left response)[2] and concluded that "priming effects are mediated by an automatic retrieval of responses that is located at an abstract or categorical level rather than at the level of specific motor responses" (p. 487). Again, the reason why Rothermund et al. found evidence of prime response retrieval in error rates may have been due to the fact that their participants were not prevented from generating probe responses (i.e., grammatical categorizations) at the time of the prime (for which they were actually required to make verbal colour categorizations). As a consequence, participants benefited from anticipating the probe response alternative when the stimulus was indeed repeated in the probe and required the same response alternative. Conversely, when prime response and prepared probe response were incompatible response alternatives, the prepared probe response alternative might have been inhibited in order to guarantee correct prime responding. After-effects of this probe response inhibition could have slowed down probe responding in the actual probe when the same word was repeated. In sum, the negative priming effects in error rates in the Rothermund et al. (2005) and in the Tipper et al. (1988) study can be assumed to have been caused by prime response information retrieved at the time of the probe. In order to test whether the absence of a negative priming effects in error rates in our Experiment 1 was caused by preventing participants from manually responding in the prime right from the start, we ran Experiment 2.

EXPERIMENT 2

Experiment 2 was a replication of Experiment 1 with the only difference that participants did not hold down the response keys during the prime presentation. If the prevention of manual prime responses in Experiment 1 was the reason why we did not find a negative priming effect in error rates, then the possibility of executing manual prime responses in Experiment 2 should yield an overall negative priming error effect.

Method

Participants

Participants were 49 adults (mostly students, 37 female). They ranged in age from 16 to 38 years ($M = 23.80$, $SD = 4.56$). None of them had participated in Experiment 1. Data of three additional participants who did not pass one of the training phases were discarded. All participants were tested individually.

Procedure

The procedure was identical to that of Experiment 1 with the only exception that participants did not have to press down the response keys during prime presentation. In Experiment 1, a photo depicting the response fingers was used to prompt participants to press down all response keys. In Experiment 2, a speech bubble was presented on the screen instead of the photo. This speech bubble reminded the participants that the next response had to be given verbally, and, additionally, it helped structuring the verbal–manual response alternation sequence in the same manner as the response-finger photo in Experiment 1. The bubble was removed from the screen after the prime response window of 2,000 ms.

Participants held their response fingers above the response keys throughout the experiment. Once in a while, participants accidentally responded manually in the prime (sometimes in addition to a verbal response). These responses

[2] To be precise, with respect to reaction times Rothermund et al. (2005) found significant positive priming in the response repetition condition but nonsignificant negative priming in the response alternation condition. For the overall error data, the significance pattern was reversed (nonsignificant positive priming in the response repetition condition, significant negative priming in the response alternation condition). The important result for testing the involvement of prime response retrieval processes is that the trial type variable significantly interacted with the response relation variable (response repetition vs. alternation) for both dependent variables.

were coded in the programme, but prime feedback was exclusively given to the accuracy of the verbal responses.

Design

The design was identical to that of Experiment 1. In Experiment 2, we were primarily interested in finding a negative priming effect in the overall errors. Given a desired level of $\alpha = .05$ (one-sided testing) and $N = 49$ participants, the power to find a negative priming effect in overall error rates of $d_z = 0.75$ (as found in Experiment 2 by Mayr & Buchner, 2006) was larger than $1 - \beta = .99$. Alternatively, a sensitivity power analysis showed that with $\alpha = .05$ and a sample size of $N = 49$, we could reveal negative priming effects as small as $d_z = 0.48$ with a statistical power of .95.

Results

Probe reaction times were evaluated only for trials with correct primes and probes. Probe errors were evaluated only if they followed a correct prime. Trials with accidentally triggered manual prime responses were excluded from the analysis (this happened in 1.87% of the ignored repetition trials and in 1.81% of the control trials). However, the pattern of results did not depend on whether these trials were excluded or not.

The means of participants' average probe reaction times (Figure 1, right side) were significantly slower in ignored repetition than in control trials, $t(48) = 4.30, p < .01, d_z = 0.61$. Participants made more errors in ignored repetition than in control trials, $t(48) = 2.58$, $p = .01$, $d_z = 0.37$ (Figure 2, right side).

The unrestricted multinomial model as displayed in Figure 3 fitted the present frequency data perfectly. The prime response retrieval parameters prr_{IR} and prr_C are illustrated in Figure 4 (right side). We tested the goodness-of-fit of the model with the restriction that $prr_{IR} = prr_C$. Although the parameter estimates were in the expected direction (prr_{IR} was somewhat larger than prr_C), the restricted model fit the data, $G^2(1) = 0.43$, $p = .51$. Thus, the hypothesis that these two parameters are equal could not be rejected.

Discussion

The results of Experiment 2 were in accordance with our expectations. We found a negative priming effect in the reaction times as in Experiment 1, but in contrast to Experiment 1, the negative priming effect was now also present in the overall error rates. Also in contrast to Experiment 1, at a descriptive level there was a tendency of committing more prime response errors in ignored repetition trials than in control trials in Experiment 2. This small increase in prime response errors in ignored repetition trials compared to control trials possibly indicates that retrieval of more or less rudimentary prime response information took place, which led to observable prime response repetition errors only in a few cases.

The most obvious explanation for the negative priming effect in the error rates in Experiment 2 is that with their fingers placed above the probe response buttons participants prepared and even started to execute more or less rudimentary manual responses but were able to inhibit these responses successfully before the invalid manual response was fully executed. As a consequence, a certain number of prime episodes can be assumed to contain information about rudimentary manual prime responses and about the inhibition of these manual responses. When this information is retrieved at the time of ignored repetition probes, it can be expected to interfere with the execution of the appropriate probe response, leading to an increase in probe response errors. As a consequence, a significant negative priming effect in the overall error rates is to be expected, which is what was observed. In contrast, a prime response retrieval effect is not necessarily expected, because the interference caused by the retrieval of rudimentary manual responses and their frequent successful inhibition should be mostly general and should not specifically favour the triggering of probe responses that repeat the attempted but suppressed prime response.

GENERAL DISCUSSION

Replicating the Tipper et al. (1988) findings from the visual modality, the auditory negative priming effect investigated here endured a change in response mode between prime and probe. In two experiments, we found a negative priming effect across response modalities in reaction times. This implies that negative priming cannot entirely be tied to specific motor responses of the stimulus. Rather, negative priming seems to be (at least) partially based on "central" processes.

Previous research has demonstrated that one mechanism underlying the negative priming phenomenon is the retrieval of task-inappropriate prime response information at the time of the probe presentation (Mayr & Buchner, 2006; Rothermund et al., 2005). For example, participants show an increase in erroneous prime responses to the probes of ignored repetition trials in comparison to the probes of control trials (Mayr & Buchner, 2006). Mayr et al. (2009) further showed that this increase in prime response errors—the so-called prime response retrieval effect—depends on motor execution of the prime response. If prime response execution is prevented, there is no prime response retrieval effect.

Of central interest to the present study was whether the prime response retrieval mechanism would endure a response modality change between verbal prime responses and manual probe responses. If we found such a prime response retrieval effect across response modality changes, then this would imply that the retrieval of prime responses takes place at the level of abstract response codes (e.g., the "piano" response). By contrast, the absence of a prime response retrieval effect across response modalities would imply that prime response retrieval takes place at the level of motor responses (e.g., the motor programme of a right index finger key press necessary to carry out the "piano" response).

The results of Experiment 1 demonstrated that a prime response retrieval effect was absent when the task required a change in response mode from verbal to manual. Participants responded equally (in)frequently with the former prime response in ignored repetition and control trials. This may mean two things: Either the change in motor response requirements from prime to probe prevents the prime response from being successfully retrieved in the probes of ignored repetition trials—perhaps due to a reduction in prime–probe similarity (e.g., Chao & Yeh, 2008)—or retrieval of a response in another response mode does not impair probe responding. In either case, this implies that response coding in terms of a task-specific response category format (e.g., use the "frog" response alternative) is not sufficient to cause prime response retrieval. In other words, the prime response retrieval effect seems to be limited to the retrieval of motor responses.

Note that we have found prime response retrieval effects in previous auditory experiments (with manual response requirement in prime and probe) in which the overall negative priming effects were approximately as large as, or even smaller than, the effect found in Experiment 1. For example, in Mayr et al.'s (2009) Experiment 1B the size of the reaction time and overall error rate effects were $d_z = 0.44$ and $d_z = 0.43$, respectively. In their Experiment 2, the size of the reaction time and overall error rate effects were $d_z = 0.35$ and $d_z = 0.21$, respectively, for go trials and $d_z = 0.42$ and $d_z = 0.27$, respectively, for invalid no-go trials), but all effects appeared in combination with significant prime response retrieval effects. This implies that the nonsignificant prime response retrieval effect of the present Experiment 1 cannot have been caused by a lower than usual size of the negative priming effect.

There was no negative priming effect in the overall error rates of Experiment 1. This finding stands in clear contrast to the overall error effects that we usually find in similar auditory negative priming experiments without a response mode change (Mayr & Buchner, 2006, Experiments 2 and 3; Mayr et al., 2009). It also seemed to be at odds with the findings of Tipper et al. (1988) and of Rothermund et al. (2005) who reported negative priming in overall errors across response mode changes. This discrepancy was assumed to be due to the fact that concurrent probe response activation (and inhibition) at the time of the prime was possible in these other experiments. By contrast, in the present Experiment 1, concurrent manual probe response activation at the time of the prime was prevented by prompting participants to press down all response keys during the prime. Experiment 2 was run to test this assumption. Participants were no longer prevented from initiating manual probe responses at the time of the prime in that they were no longer required to hold down the response keys during the prime presentation. As expected, a negative priming effect appeared in the overall error rates in Experiment 2. The most obvious way to explain this finding is to assume that participants prepared and started to execute more or less rudimentary additional manual responses in a certain number of prime trials. Full execution of these erroneous manual prime responses was successfully inhibited in most of these trials, which fits with the fact that there was only a very small percentage of accidental manual prime responses. A certain number of prime episodes can thus be assumed to contain information about rudimentary manual prime responses and about the inhibition of these manual responses. When this information is retrieved at the time of ignored repetition probes, it can be expected to interfere with the execution of the appropriate probe response, leading to an increase in probe response errors in Experiment 2 that could not have been observed in Experiment 1.

Although there was a negative priming effect in error rates in Experiment 2, there was only a weak, nonsignificant tendency of a prime response retrieval effect—that is, the number of prime response errors increased only very slightly in ignored repetition compared to control trials. Note that there was only a very small number of prime trials with manual responses, but presumably a large number of prime trials for which responses had been prepared but were then successfully inhibited. As a consequence, the vast majority of the prime episodes retrieved at the time of the probe should include rudimentary prime response information in association with response inhibition information. Retrieving this information should cause general interference and should not specifically favour the triggering of probe responses that repeat the attempted but suppressed prime response.

The combined pattern of results from Experiment 1 and Experiment 2 suggests that the negative priming effect in overall errors is primarily, if not exclusively, due to the retrieval of task-inappropriate prime response (execution and inhibition) information. If the mechanism does not operate—for example, after response mode changes and while preventing prime response executions as in the present Experiment 1—then the negative priming effect in overall errors vanishes. In contrast, negative priming in response speed was not substantially modulated by prime response retrieval processes although the effect size of the negative priming effect in reaction times increased from $d_z = 0.46$ in Experiment 1 to $d_z = 0.61$ in Experiment 2. This suggests that reaction time negative priming effects may, to a large extent, be due to mechanisms other than prime response retrieval, such as nonresponse retrieval (Neill & Valdes, 1992) or inhibitory processes (Houghton & Tipper, 1994; Tipper, 1985, 2001) or both. Alternatively, it could be that reaction time effects are more robust than error effects.

Tipper et al. (1988) reported that the negative priming effect in their experiment was unaffected in size by whether or not participants changed response modes between prime and probe. For instance, negative priming was equivalent in size for a verbal–manual and a manual–manual condition. In the present experiments, we had to abstain from running a manual–manual group. This had to be so in Experiment 1 because we intentionally prevented unintended manual prime responses by prompting participants to press down all response keys, and therefore a manual–manual group would no longer be comparable. Experiment 2 was run as a control experiment to Experiment 1 and was therefore kept maximally parallel to Experiment 1, so that the manual–manual group had to be omitted as well. As a consequence, we can only indirectly compare the size of the negative priming effects under the present response mode change conditions and the no-change conditions in related experiments. The size of the negative priming effect in reaction times in the present Experiment 1 (in which manual prime responses were impossible) was $d_z = 0.46$ and thus somewhat smaller than the negative priming effect found with the same stimulus material and task but without a response mode change ($d_z = 0.75$; Mayr & Buchner, 2006, Experiment 2). Obviously, the negative priming effect is smaller across than within response modalities. This implies that peripheral motor components (absent under response mode change conditions) as well as central processes (present under response mode change conditions) are involved in the phenomenon.

In sum, our findings allow for the conclusion that prime response retrieval depends on retrieval of motor responses. If the motor response requirements change between prime and probe, there is no longer an increase of errors in ignored repetition trials whereas the negative priming response slow-down does not seem to be crucially dependent on this retrieval process.

Original manuscript received 15 December 2008
Accepted revision received 23 May 2009
First published online 22 July 2009

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