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Separating after-effects of target and distractor processing in the tactile sensory modality

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Abstract
The present study investigated the cognitive mechanisms underlying aftereffects of tactile target and distractor processing. In our experiment, participants selected tactile target stimuli against simultaneously presented tactile distractor stimuli in prime–probe sequences. Tactile distractors in each prime/probe trial were either response incompatible (i.e., interfering at the response level) or response neutral (i.e., noninterfering at the response level), manipulated between participants. Furthermore, distractor relation (repetition vs. change) and response relation (repetition vs. change) across prime–probe sequences were orthogonally varied within participants. Thus, independent estimates of distractor repetition main effects (that are attributable to distractor-specific prime processing and have previously been interpreted in terms of inhibition or episodic retrieval processes) and the modulation of distractor repetition effects due to response relation (that is target specific and can only be explained in terms of event-file retrieval) were assessed (see Giesen, Frings, & Rothermund, *Memory & Cognition, 40,* 373–387, 2012). Replicating previous studies with visual stimuli, simple distractor repetition effects were stronger for response-incompatible compared with response-neutral tactile distractors. In contrast, event-file retrieval as reflected in distractor-response binding retrieval effects was not modulated by whether the distractors were response incompatible or response neutral. Together, these findings highlight that in tactile tasks, prime-distractor and prime-target processing both hold the potential to cause aftereffects during probe performance.

Keywords Distractor-response binding · Distractor inhibition · Episodic retrieval · Touch

Our tactile sense is of central importance in everyday life: Tactile stimuli are ubiquitous and indispensable for a multitude of goal-directed behaviors (e.g., steering a car; finding your keys in your bag) and also for social interactions (e.g., shaking hands, caressing a loved one). Moreover, new technologies increasingly use tactile signals and tactile feedback in the interaction between a user and a device. However, it is almost never the case that only one tactile stimulus has an impact on our skin at a given moment. In many situations, multiple tactile stimuli are encoded at the same time, although

in the majority of cases only few of these are directly relevant for the task or goal at hand, meaning that most of these tactile stimuli need to be ignored. To be able to understand and predict human behavior in such situations, it is crucial to understand the mechanisms involved in handling irrelevant tactile stimuli.

Previous research has demonstrated that distractors in a tactile task cause interference in a similar way as distractors in visual, auditory, and olfactory tasks. That is, the processing of a tactile target is hindered at the perceptual as well as at the response level when a tactile distractor is simultaneously presented (e.g., Craig, 1974, 1995, 2000; Frings & Spence, 2010; Uttal, 1960; Wesslein, Spence, & Frings, 2014). Moreover, ignoring a tactile distractor can affect subsequent performance: It has been shown that responses toward a tactile stimulus are impeded if this stimulus has previously been ignored. That is, when a distractor stimulus of one trial (the *prime*) is repeated as target stimulus on the subsequent trial (the *probe*)—which is the case in the so-called ignored repetition condition of the negative priming (NP) paradigm, then probe

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performance is slower and/or more error prone, compared with a control condition without stimulus repetitions. Such NP effects have been documented for tactile stimuli (Frings, Amendt, & Spence, 2011; Frings, Bader, & Spence, 2008; Wesslein, Spence, Mast, & Frings, 2016), for stimuli of other sensory modalities (e.g., visual: Tipper, 1985; auditory: Mayr & Buchner, 2007; olfactory: Olsson, 1999), as well as across different stimulus modalities (audiovisually: Buchner, Zabal, & Mayr, 2003).

The problem with NP is that these aftereffects of the processing of ignored distractor stimuli can be explained by different mechanisms (for a recent overview, see Frings, Schneider, & Fox, 2015). A coarse-grained distinction differentiates accounts that predominantly focus on aftereffects of distractor processing from those focusing on aftereffects of target-specific processing. We briefly lay out both accounts in turn.

Aftereffects of distractor-specific processing

The most prominent explanations of NP can be understood as dealing with aftereffects arising from distractor processing during the prime trial. These theories focus on distractor inhibition (e.g., Houghton & Tipper, 1994; Tipper, 1985) or episodic response retrieval (Neill, Valdes, Terry, & Gorfein, 1992; Rothermund, Wentura, & De Houwer, 2005): According to the distractor-inhibition account (Neill, 1977; Tipper, 1985), to-be-ignored distractors become inhibited during the prime trial to facilitate prime target selection (Tipper & Cranston, 1985). It is assumed that inhibition of the prime distractor persists to the probe trial. Thus, if the prime distractor becomes the probe target, probe performance is impaired (i.e., NP is observed), compared with the control condition without stimulus repetitions - presumably due to the persistence of distractor inhibition. According to episodic retrieval accounts, NP effects may result from an automatic retrieval of a "do not respond" tag encoded with the distractor during prime processing (see Neill et al., 1992), which slows down probe performance.

It is important to note that there is no easy way to dissociate between episodic retrieval and inhibition processes in the NP paradigm, because the repetition of the prime distractor as probe target stimulus is confounded with a change of responses between prime and probe trials in the classical variant of the NP task. Nonetheless, the wide range of obtained NP effects are difficult to explain for either inhibition or episodic retrieval accounts alone (see Frings et al., 2015). By now, there is consensus that aftereffects of distractor processing can be caused by either mechanism. It is reasonable to assume that this also holds for tactile NP, though the mechanism underpinning aftereffects of ignoring in the tactile sensory modality have not yet been as extensively studied as visual and auditory NP.

Aftereffects of target-specific processing: Incidental distractor-response bindings

Aside from distractor-specific processing, target-specific processing that takes place during the prime trial may also impact probe performance due to episodic retrieval. Specifically, even if the prime target is simply accompanied by a distractor, executing a response toward the prime target may result in incidental bindings between this distractor and the prime response. Following the theory of event coding (Hommel, Müsseler, Aschersleben, & Prinz, 2001), triggered by the repetition of any of the bound features, this binding of stimulus and response features may subsequently be retrieved. Accordingly, the repetition of the prime distractor in the probe may lead to automatic retrieval of incidental episodic distractor-response bindings—reflecting aftereffects of target-specific processing (e.g., Frings, Rothermund, & Wentura, 2007; Rothermund et al., 2005). If the retrieved prime response is inappropriate in the probe (which is also the case in the ignored repetition condition of the NP paradigm, i.e., when the prime distractor—after being bound to the prime response—is repeated as the probe target), probe performance is impaired (Rothermund et al., 2005).

Dissociating aftereffects of prime-target and prime-distractor processing

To gain more insight on the processes underlying aftereffects of stimulus processing in the visual domain, Giesen, Frings, and Rothermund (2012) recently introduced a variant of the distractor-response binding task (e.g., Frings et al., 2007), which enables the assessment of two independent types of sequential effects, namely target-specific and distractor-specific aftereffects. In their task, participants select target letters from flanking, to-be-ignored distractor letters (e.g., JKJ) across a sequence of prime and probe trials. Compared with the NP paradigm, two important changes are noteworthy: Giesen and colleagues used a sequential distractor-to-distractor repetition paradigm. First, probe performance in prime–probe sequences in which the prime distractor also serves as the probe distractor (i.e., distractor repetition; e.g., JKJ → JKJ; JFJ → JKJ) is compared with probe performance in sequences with a novel probe distractor (i.e., distractor change; e.g., DKD → JKJ; DFD → JKJ; see also Fig. 1a). Typically, performance is faster in distractor repetition probes than in distractor change probes. Giesen and colleagues interpret this simple distractor repetition effect as an indicator of distractor inhibition. Accordingly, in distractor repetition trials, inhibition of the prime distractor may carry over to the probe and thus facilitate probe target selection (because the distractor is still inhibited in the probe), compared with probe trials with a novel (i.e., not-yet-inhibited) distractor (Frings &

Fig. 1 Experimental design and sample stimuli for prime-probe sequences belonging to the response-incompatible distractor set. For the response-neutral distractor set (not pictured for reasons of brevity), Stimuli 5 to 8 were used as distractors instead of Stimuli 1 to 4 (see Fig. 2). DC = distractor change; DR = distractor repetition; RR = response repetition; RC = response change. **a** Distractor repetition (DRep) effects were computed as the difference between DC minus DR, averaged across the response relation factor, that is, DRep = (DCRR + DCRC)/2 − (DRRR + DRRC)/2, for each distractor set. Positive values indicate faster probe performance in DR trials. **b** Effects due to episodic retrieval of distractor-response bindings (DRB), computed from Distractor Relation × Response Relation interaction effects in the probe, that is, the double difference between (DC minus DR) in RR versus RC conditions: DRB retrieval effect = (DCRR − DRRR) − (DCRC − DRRC). Positive values indicate interaction effects that conform with expected effects due to distractor-based retrieval of previous responses: That is, performance *benefits* (i.e., positive DRB retrieval effects) for probe trials belonging to response repetition sequences and performance *costs* (i.e., negative DRB retrieval effects) for probe trials belonging to response change sequences

Wühr, 2007; Neumann & DeSchepper, 1991; Yashar & Lamy, 2010). As mentioned earlier, other interpretations of simple distractor repetition effects are possible. For instance, distractor repetition effects may also result from the episodic retrieval of "do not respond" tags (Neill et al., 1992) that were stored in the prime episode. Retrieval of these tags in distractor repetition probe trials would speed up selection of the probe target due to reduced interference or response conflict, compared with trials with a novel distractor (Neill & Valdes, 1992; Neill et al., 1992).

Contributions of episodic retrieval and distractor inhibition to distractor repetition effects cannot be disentangled within the distractor-response binding task. More importantly, though, both of these aftereffects of distractor processing operate independently from response-execution requirements that are related to target-specific processing (i.e., their effects are independent of whether the same or a different response is required in prime and probe trials). Specifically, the aftereffects of distractor processing are reflected in *simple* distractor repetition effects observed in probe trials with distractor repetitions compared with probe trials with distractor changes (averaged across response repetitions or changes), respectively. In statistical terms, aftereffects of distractor processing are therefore indicated by a main effect of distractor relation.

The second important change incorporated by Giesen et al. (2012) concerns the removal of the confound between distractor repetitions and response repetitions/changes across prime and probe trials, which is imminent in the NP paradigm. In the sequential distractor repetition paradigm, aftereffects of target-specific processing—which are indicated by retrieval of incidental distractor-response bindings—are assessed by repeating or changing the targets/responses between prime and probe trials (i.e., a target-related manipulation) independently from repeating or changing the distractors between prime and probe trials. Related to the theory of event coding (Hommel et al., 2001), the underlying reasoning is that during the prime trial, the distractor becomes incidentally associated with the response executed in response to the prime target. Repetition of a prime distractor as a probe distractor should then lead to the retrieval of the prime response. Depending on whether the required response repeats or changes from prime to probe, retrieval of the prime response (due to retrieval of distractor-response binding built during prime processing) differentially affects probe performance (e.g., Frings & Rothermund, 2011; Frings et al., 2007; Mayr & Buchner, 2006; Rothermund et al., 2005). Specifically, retrieval of the executed prime response facilitates probe performance if the same response is required in the probe. Hence, distractor repetitions should enhance probe performance in this case (e.g., better performance in the sequence JKJ → JKJ compared with DKD → JKJ). In contrast, if the prime response does not represent the appropriate probe response—that is, when the required response changes from prime to probe—then retrieval of the executed

prime response causes interference. Thus, in response change sequences, probe performance should be impaired if the distractor is repeated (e.g., worse performance in the sequence JFJ → JKJ compared with DFD → JKJ).

In statistical terms, aftereffects of target-related processing, reflected in effects caused by the retrieval of distractor-response bindings (DRB), are indicated by an interaction of the factors response relation and distractor relation (see Fig. 1b): More facilitation of probe responses due to distractor repetition (as compared with distractor change) is expected for response repetition than for response change sequences. That is, DRB effects are computed by subtracting distractor repetition benefits in response change sequences from distractor repetition benefits in response repetition sequences (see Fig. 1b for details on effect computation). Note that it is essential to always test DRB effects via this interaction.

In order to demonstrate that two types of effects can be independently assessed within their task, Giesen et al. (2012) manipulated the interfering potential of distractors. Whereas no response was associated with those stimuli serving as response-neutral (i.e., noninterfering at the response level) distractors, response-incompatible distractors were mapped onto a response, thus holding the potential to cause interference during target selection at the response level (see Eriksen & Eriksen, 1974). Along with the inhibition account, Giesen et al. (2001) assumed that distractor inhibition is a function of response interference (Grison & Strayer, 2001; Houghton, Tipper, Weaver, & Shore, 1996), thus expecting response-incompatible distractors to receive stronger inhibition than response-neutral distractors during the prime trial. Consequently, distractor repetition benefits in the probe trial were expected to be stronger for response-incompatible compared with response-neutral distractors due to these differences in the magnitude of distractor inhibition. In line with the prediction, simple distractor repetition benefits were always stronger for response-incompatible compared with response-neutral distractors (reflected in a Distractor Relation × Distractor Set interaction) in two experiments. Yet, turning to the size of episodic DRB effects, Giesen et al. (2012) observed no differences for the response-neutral and response-incompatible distractor sets (reflected in a significant Distractor Relation × Response Relation interaction that was not further qualified by distractor set). This indicates that the manipulation of distractor set activates selective attentional processes that, however, do not prevent the distractors from being bound to the executed prime response and from retrieving this response at a later occasion. The aftereffects related to distractor processing might thus function independently from aftereffects of target-induced processing. Note that the interpretation of the main effect of distractor relation to reflect distractor inhibition is based on the assumption that the opposite effects of distractor response binding on response

repetition and response change sequences affect performance to roughly the same amount and thus neutralize each other.

Implemented in the tactile stimulus modality, the described paradigm and method represent a straightforward tool to investigate aftereffects of distractor-induced and target-induced information processing in the tactile sensory modality. Importantly, DRB has been shown to function similarly in the visual (Frings & Rothermund, 2011; Frings et al., 2007; Giesen & Rothermund, 2011), auditory (Mayr & Buchner, 2006; Moeller, Rothermund, & Frings, 2012), and tactile (Moeller & Frings, 2011) stimulus modalities. Furthermore, DRB effects are also documented across different stimulus modalities (e.g., visual-auditory; Frings, Moeller, & Rothermund, 2013), indicating that DRB effects are conceptually mediated. Against this background, it seems reasonable to assume that the previous findings from vision and audition will replicate in the current study with tactile stimuli. Then again, tactile cortical pathways differ from visual pathways in their organization (Dijkerman & de Haan, 2007). While visual pathways are typically assumed to be divided into *what* and *where* (e.g., DeYoe & Van Essen, 1988; Mishkin, Ungerleider, & Macko, 1983; Treisman, 1996) or *what* and *how* pathways (Goodale & Milner, 1992; Milner & Goodale 1995), such a clear distinction is not possible for tactile pathways (Dijkerman & de Haan, 2007; Drewing & Schneider, 2007). In addition, the NP effect has been shown to be larger in tactile as compared with visual setups—even when stimulus factors (i.e., differences in the processing difficulty between tactile and visual stimuli) were controlled for (Frings et al., 2011). It is therefore unclear whether episodic binding and retrieval processes related to target processing play a similar role in tactile distractor encoding as in visual distractor encoding, or whether the relevance of target-specific and distractor-specific sequential effects is distributed differently in the two sensory modalities.

The present study: Disentangling aftereffects of target-specific and distractor-specific processing in the tactile sensory modality

In the current study, we aimed to implement a tactile variant of the sequential distractor repetition paradigm (see Giesen et al., 2012, Experiment 1) to disentangle distractor-related and target-related aftereffects in touch. In each trial, participants had the task to identify a tactile target stimulus and select it against a simultaneously presented tactile distractor stimulus; participants performed this task in a sequence of prime and probe trials. The tactile distractors were either drawn from the same stimulus set as target stimuli, meaning they were response incompatible (i.e., interfering at the response level) or were sampled from a different stimulus set and therefore response neutral (i.e., noninterfering at the response level).

Furthermore, distractor relation (repetition vs. change) and response relation (repetition vs. change) across prime–probe sequences were independently manipulated. Assuming that the similar processes underpin distractor information processing in the tactile and the visual modality, the findings of Giesen et al. (2012) should replicate in our study. In particular, we predicted stronger distractor repetition effects for response-incompatible than for response-neutral distractors (i.e., better performance in trials with distractor repetition compared with distractor change, especially with the response-incompatible distractor set, reflected in an interaction of distractor set and distractor relation). In contrast, we predicted DRB retrieval effects to emerge regardless of the distractor set (i.e., performance benefits due to DRB retrieval if the prime response is also repeated in the probe; performance costs due to DRB retrieval if the response changes from the prime to the probe), manifesting in an interaction of the factors of distractor relation and response relation. Importantly, we expected no difference in the size of DRB retrieval effects as a function of distractor set. Together, these findings would indicate that cognitive processes associated with distractor processing and with target processing independently elicit aftereffects in tactile information processing.

Method

The current experiment was carried out in accordance with the Declaration of Helsinki and its later amendments. Informed consent was obtained from all individual participants included in the study.

Participants

Seventy-one students participated, all having normal or corrected-to-normal vision. Data from one participant were excluded from the analyses because her mean accuracy rate constituted an outlier according to Tukey (1977) when compared with the sample distribution of the mean accuracy rate of all participants within the same experimental condition (i.e., three interquartile ranges below the third quartile of the overall distribution). Thus, data of $N = 70$ participants (58 female) with a median age of 21 years (ranging from 18 to 42 years) were analyzed. The difference in distractor repetition effects and DRB retrieval effects between both groups was relevant for a priori power considerations. In order to detect a medium-sized within–between interaction effect ($f_z = 0.25$; cf. Cohen, 1969), assuming a strong correlation ($r = .60$) among the repeated measures and desired levels of $\alpha = \beta = .05$, data had to be collected from a sample of at least $n = 30$ participants per condition (calculations were performed with G*Power Version 3.1.3; Faul, Erdfelder, Lang, & Buchner, 2007). We

were able to collect data from $n = 35$ participants per condition, yielding an even higher achieved power of $1 - \beta = .98$.

Design

The experiment consisted of a 2 (response relation: response repetition vs. response change) × 2 (distractor relation: distractor repetition vs. distractor change) × 2 (distractor set: response-incompatible, $n = 35$ vs. response-neutral, $n = 35$) mixed-factorial design with repeated measures on all experimental factors but distractor set, which was manipulated between participants.

Apparatus and materials

The experiment was conducted on a PC with a 24-in. TFT screen using a standard computer keyboard. It was run by E-Prime 2.0 software, which also controlled the presentation of the vibrotactile stimuli via a serial interface. That is, the vibrotactile stimuli were delivered by means of two tactors (Model C-2, Engineering Acoustic, Inc.) which were driven independently from the PC by an individual standard amplifier (Power Amplifier Module PM40C, t.amp). Each tactor was 1.17-in. in diameter and 0.30-in. thick, and they were fastened to the side of the participant's left and right palms by means of Velcro strips.

Throughout the experiment, eight 1,000-ms vibrotactile stimuli with different rhythms were used (see Fig. 2 for a schematic illustration). The first vibration consisted of one 1,000-ms pulse without pauses. The second vibration comprised two 100-ms pulses, separated by one 200-ms and another 600-ms pause. Intermittent 100-ms pulses and 100-ms pauses constituted the third vibration. The fourth vibration comprised one 200-ms pulse, followed by an 800-ms pause, while the fifth vibration comprised two 100-ms pulses separated by one 200-ms pulse with each pulse being followed by a 200-ms pause. The sixth vibration consisted of four 100-ms pulses, separated by three pauses of equal length as well as one pause of 300 ms. The seventh and eighth vibration each comprised two pulses. Yet, while those lasted for 300 ms and were separated by one 300-ms and one 100-ms pause for one vibration, they lasted for 200 ms and were both followed by a 300-ms pause for the last vibration. Stimuli 1 to 4 were mapped onto separate response keys (one-to-one mapping), thus serving as targets and also as response-incompatible distractors, whereas Stimuli 5 to 9 were not mapped onto responses, and thus served as response-neutral distractors.

Procedure

The experiment was conducted individually in 60-min sessions in a completely light-proofed and sound-proofed room. Participants sat approximately 60 cm from the computer screen with their head positioned on a chin rest so that head orientation was constant. Their wrists were placed on armrests, and they were presented white noise via headphones. Both these precautions were taken to limit and control for any potential auditory cues emitted by the
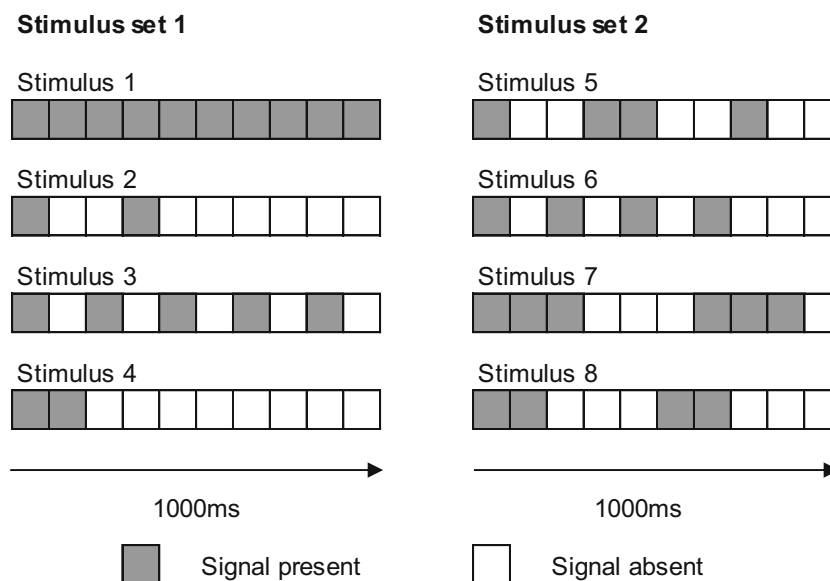
Fig. 2 Schematic illustration of the eight different rhythms used in the current experiment, each consisting of ten 100-ms intervals. Stimulus Set 1 (mapped onto the response keys D, C, J, and N) served as the target set. For the response-incompatible distractor condition, Stimulus Set 1 also served as the distractor set, whereas Stimulus Set 2 served as the distractor set for the response-neutral condition. Note that each rhythm was repeated every 1,000 ms until a response was detected or 5,000 ms had elapsed. The rhythms were delivered to the participant's hands as vibrations by means of skin transducers

operation of the transducers. The task instructions were presented on the computer screen and were also shortly summarized by the experimenter; responses involved presses of the keys D, C, J, and N on the computer keyboard with the left middle and index fingers as well as the right middle and index fingers. These keys were marked with green stickers.

At the beginning of the experimental session, the participants were familiarized with the four tactile vibrations used as the target vibrations throughout the experiment and learned the assignment of each vibration to one of the four response keys. Thus, participants were instructed to position their middle and index fingers on the designated keys, and each vibration was accompanied with a picture of two hands on the screen. On this picture, the finger to be used to execute the correct response was colored green. In each trial, the vibration followed a 300-ms fixation cross presented on the screen, and it was repeatedly presented until a response was detected or until 5,000 ms had elapsed. In this learning phase, each vibration was presented five times together with the picture indicating the correct response. The presentation order was randomized.

In the following practice phase, each trial comprised two different vibrations, which were simultaneously presented to the participants' right and left hand. Participants' task thus was to respond to the target vibration (which was again accompanied by the picture indicating the correct response) while ignoring the distractor vibration. The to-be-selected target vibration was indicated by the stimulus position. In particular, participants were randomly assigned to one of two conditions: Half of the participants had to respond to the stimulus presented to the left hand while the other half of the participants had to respond to the stimulus presented to the right hand. For each participant, the target position remained constant throughout the experiment to allow the allocation of (covert) spatial attention specifically to the target hand. Again, each trial started with the presentation of a fixation cross for 300 ms. Then the presentation of the target and distractor vibrations started, accompanied with the picture indicating the correct response and lasting until the participant responded (or until 5,000 ms elapsed). The trial ended with the presentation of a blank black screen lasting 500 ms. Note that later in the experimental session, when there was no longer a pictorial performance aid during stimulus presentation, the fixation cross remained on the screen while the tactile target and distractor stimuli were presented. Throughout the experiment, targets and distractors were always nonidentical in a given trial. Each possible stimulus combination was presented twice, resulting in a total of 24 trials (2 × 4 target vibrations × 3 distractor vibrations) for the response-incompatible distractor set and a total of 32 trials (2 × 4 target vibrations × 4 distractor vibrations) for the response-neutral distractor set. Participants were told to remember the assignment of the target vibrations to the

response keys and were told that the picture aid would no longer be presented in following phases.

In the next practice phase, the prime–probe design was introduced, so participants familiarized with the final experimental trial procedure. Each trial started with the presentation of a black screen with the instruction to press the space key to start a "double trial" (i.e., prime–probe sequence), presented in white font color. When a participant thus self-initiated the presentation, the 300-ms presentation of a fixation cross was followed by the vibrotactile prime target and prime distractor until the participant responded or until 5,000 ms had elapsed. Next, participants received feedback on the screen: For correct/incorrect responses, the message "correct"/"sorry, this response was wrong" was presented in green/red font color. If 5,000 ms elapsed without a response being detected, the message "please respond faster" was presented in white font color. Feedback regarding prime performance was presented for 1,500 ms, followed by the presentation of another fixation cross (300 ms), the probe target and distractor stimuli (presented until response or until 5,000 ms had elapsed), and feedback regarding probe performance (probe feedback was given in a similar way as prime feedback). Then, participants could initiate the next prime–probe sequence by pressing the space key. In this last practice phase, participants went through 36 prime–probe sequences, which were randomly selected from the set of possible prime–probe sequences (all of which were presented during the experimental phase).

With regard to the procedure, the experimental phase resembled the preceding practice phase with the exception that feedback was presented only following incorrect or exceedingly slow responses (more than 5,000 ms). Here, participants were presented with 256 prime–probe sequences. These were set up similarly to Giesen et al. (2012, Experiment 1) with respect to the experimental design, that is, with specific restrictions for the response-incompatible distractor set. In detail, (a) response-incompatible distractors were always different from the target, (b) prime targets were never repeated as probe distractors, and (c) prime distractors were never repeated as probe targets. Moreover, the response was repeated from the prime to the probe on 25% of all trials (response repetition; RR), whereas responses changed on 75% of all trials (response change; RC). Similarly, the distractor was repeated from the prime to the probe on 25% of all trials (distractor repetition; DR), whereas it changed on 75% of all trials (distractor changes; DC). This was done to guarantee that neither response nor distractor repetitions violated base rate expectations of distractor and/or response repetitions/changes. This resulted in 16 DRRR, 48 DRRC, 48 DCRR, and 144 DCRC trials. After the experiment, participants were thanked and received course credit for their participation.

Results

Probe reaction times (RTs) were the primary dependent variable. For the RT analyses, only prime–probe sequences with correct responses in both the prime and the probe trials were used. In detail, prime–probe sequences with response omissions (0.4%), with erroneous responses in the prime and/or probe (34.1%; see Wesslein et al., 2016, for a comparably high error rate in a tactile experiment with a prime–probe design; this is presumably attributable to the participant's raw experience with unimodal tactile tasks), or with RT outlier values[1] (0.8%) were excluded from analyses. For all of the statistical analyses reported here, a significance level of $\alpha = .05$ was specified.

Average probe RTs

For each participant, average probe RTs were computed for every condition of the factorial design (see Table 1). These means were submitted to a mixed-models $2 \times 2 \times 2$ multivariate analysis of variance (MANOVA) with the within-participants factors response relation (response repetition vs. response change) and distractor relation (distractor repetition vs. distractor change), and with the distractor set (response incompatible vs. response neutral) manipulated between participants (see O'Brien & Kaiser, 1985, for the use of MANOVA to analyze repeated-measures designs). The main effects of response relation, $F(1, 68) = 84.43$, $p < .001$, $\eta_p^2 = .55$, distractor relation, $F(1, 68) = 4.66$, $p = .034$, $\eta_p^2 = .06$, and distractor set, $F(1, 68) = 7.32$, $p = .009$, $\eta_p^2 = .10$, were all significant. Responses were faster in sequences with response repetition ($M = 1,106$ ms, $SE = 35$ ms) compared with response change ($M = 1,281$ ms, $SE = 37$ ms), and in sequences with distractor repetition ($M = 1,179$ ms, $SE = 35$ ms) compared with distractor change ($M = 1,208$ ms, $SE = 36$ ms). Additionally, RTs in trials with response-neutral distractors were shorter ($M = 1,104$ ms, $SE = 34$ ms) than RTs in trials with response-incompatible distractors ($M = 1,283$ ms, $SE = 57$ ms). These effects were qualified by several interactions. First, the Distractor Relation × Distractor Set interaction was significant, $F(1, 68) = 4.63$, $p = .035$, $\eta_p^2 = .06$. To follow up on this interaction, we computed distractor repetition effects (DRep effects) for each distractor set as the difference of distractor change minus distractor repetition probes, averaged across response relation (DRep = [DCRR + DCRC]/2 − [DRRR + DRRC]/2). Distractor repetition effects represent simple main effects of distractor relation within each distractor set condition (positive values indicate stronger distractor

repetition benefits; see also Fig. 3a). As predicted, simple distractor repetition effects were stronger for response-incompatible (DRep = 57 ms, $SE = 22$ ms) than for response-neutral distractors (DRep = 0 ms, $SE = 15$ ms). Furthermore, the size of distractor repetition effects differed significantly from zero for response-incompatible distractors, $t(34) = 2.58$, $p = .014$, $d_z = 0.44$; but not for neutral distractors, $t(34) = 0.01$, $p = .995$, $d_z = 0.001$. Second, the Distractor Relation × Response Relation interaction was significant as well, $F(1, 68) = 5.58$, $p = .021$, $\eta_p^2 = .08$, indicating retrieval of distractor-response bindings from the prime trial. To follow up on this interaction, we computed distractor repetition effects individually for response repetition and response change conditions. The data showed the typical DRB retrieval pattern: Compared with distractor change, distractor repetition produced a performance benefit in response repetition probes and led to significantly faster responses ($\Delta_{\text{DCRR-DRRR}} = 63$ ms, $SE = 22$ ms), $t(69) = 2.87$, $p = .005$, $d_z = 0.34$. In turn, in response-change sequences, distractor repetition produced performance costs compared with distractor change ($\Delta_{\text{DCRC-DRRC}} = -5$ ms, $SE = 17$ ms); however, this slowing of responses was not statistically significant, $t(69) = -0.31$, $p = .758$, $d = 0.04$. Most importantly, the three-way interaction of distractor relation, response relation, and distractor set was not significant, $F(1, 68) = 0.12$, $p = .734$, $\eta_p^2 = .002$, indicating that the size of DRB retrieval effects did not differ as a function of the distractor set (see Fig. 3b). Likewise, the interaction of distractor set and response relation was not significant, $F(1, 68) = 0.63$, $p = .432$, $\eta_p^2 = .01$.

Error rates

For the analyses of the probe error data, only sequences with correct prime responses were considered. Individual probe error rates (see Table 1) were subjected to the same 2 (response relation: response repetition vs. response change) × 2 (distractor relation: distractor repetition vs. distractor change) × 2 (distractor set: response incompatible vs. neutral) MANOVA. Significant main effects of response relation, $F(1, 68) = 87.31$, $p < .001$, $\eta_p^2 = .56$, and distractor relation, $F(1, 68) = 25.09$, $p < .001$, $\eta_p^2 = .27$, were observed. That is, participants made fewer errors in sequences with response repetition ($M = 13.2\%$, $SE = 1.5\%$) compared with sequences with response change ($M = 24.8\%$, $SE = 2.1\%$), and in sequences with distractor repetition ($M = 16.3\%$, $SE = 1.6\%$) compared with sequences with distractor change ($M = 21.7\%$, $SE = 2.0\%$). These effects were qualified by the following interactions: First, there was a significant interaction between distractor relation and distractor set, $F(1, 68) = 6.80$, $p = .011$, $\eta_p^2 = .09$, reflecting stronger distractor repetition effects for response-incompatible distractors (DRep = 8.3%, $SE = 1.9\%$) than for response-neutral distractors (DRep = 2.6%, $SE = 1.1\%$; see Table 1). The size of distractor repetition effects

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[1] Probe RTs below 200 ms or more than three interquartile ranges above the third quartile of the overall individual RT distribution were regarded as outliers (`Tukey, 1977). Only probe RTs in sequences with correct prime and probe responses were considered.

Table 1 Mean probe RTs (in ms) and error rates (in %) as a function of response relation, distractor relation, and distractor set (standard errors in parentheses)

Distractor set	Distractor relation	Probe RTs (ms)		Probe errors (%)	
		Response relation		Response relation	
		RR	RC	RR	RC
Response incompatible ($n = 35$)	DR	1155 (58)	1354 (64)	8.0 (2.2)	26.2 (3.1)
	DC	1252 (62)	1372 (59)	24.2 (3.4)	26.6 (3.4)
	DRep effect	57 (22)		8.3 (1.9)	
	DRB retrieval effect	78 (48)		15.9 (2.7)	
Response neutral ($n = 35$)	DR	994 (34)	1213 (43)	8.6 (1.9)	22.3 (2.9)
	DC	1023 (36)	1184 (39)	12.0 (1.8)	24.2 (3.0)
	DRep effect	0 (15)		2.6 (1.0)	
	DRB retrieval effect	58 (32)		1.4 (2.7)	

DR = distractor repetition; DC = distractor change; RR = response repetition; RC = response change. DRep effect = distractor repetition effect, computed as the difference between DC and DR, averaged across response relation, that is, DRep = (DCRR + DCRC)/2 − (DRRR + DRRC)/2. Positive values indicate probe performance benefits due to repeating a persistently inhibited distractor from the preceding prime trial. DRB retrieval effect = effects due to retrieval of distractor-response bindings, computed as the difference between DC and DR between the RR and RC conditions, that is, DRB retrieval effect = (DCRR − DRRR) − (DCRC − DRRC). Positive values indicate interaction effects that conform with expected effects due to distractor-based retrieval of previous responses (i.e., positive DRB retrieval effects for response repetition sequences and negative DRB retrieval effects for response change sequences)

differed significantly from zero for response-incompatible and response-neutral distractors, $t(34) = 4.36$, $p < .001$, $d_z = 0.74$, and $t(34) = 2.46$, $p = .019$, $d_z = 0.42$, respectively. Second, a significant interaction of response relation and distractor relation was observed, $F(1, 68) = 20.33$, $p < .001$, $\eta_p^2 = .23$, indicating retrieval of episodic distractor-response bindings. Compared with distractor change, distractor repetition produced a performance benefit in response repetition probes and led to significantly fewer errors ($\Delta_{DCRR-DRRR} = 9.8\%$, $SE = 1.9\%$), $t(69) = 5.11$, $p < .001$, $d_z = 0.61$. In turn, distractor relation had no effect on response change sequences ($\Delta_{DCRC-DRRC} = 1.1\%$, $SE = 1.0\%$), $t(69) = 1.06$, $p = .295$, $d_z = 0.13$. Finally, and in contrast to the pattern of effects reflected in RTs, the three-way interaction of distractor relation, response relation, and distractor set was significant as well, $F(1, 68) = 14.17$, $p < .001$, $\eta_p^2 = .17$. To follow up on this three-way interaction, we computed two 2 (distractor relation) × 2 (response relation) MANOVAs for each level of the distractor-set factor. These analyses revealed that episodic DRB retrieval effects were only significant for response-incompatible distractors (Distractor Relation × Response Relation interaction): $F(1, 34) = 33.77$, $p < .001$, $\eta_p^2 = .50$; net DRB retrieval effects were computed as the double difference of (distractor change minus distractor repetition) in response repetition minus (distractor change minus distractor repetition) in response change sequences (i.e., net DRB retrieval effect = [DCRR − DRRR] − [DCRC − DRRC]), resulting in net DRB retrieval effect = 15.8% (see also Table 1), but not for neutral distractors (Distractor Relation × Response Relation

interaction): $F(1, 34) = 0.28$, $p = .599$, $\eta_p^2 = .01$; net DRB retrieval effect = 1.5%.[2] No other effect was significant (all Fs < 1.71, all ps > .196).

Discussion

The present study sought to investigate the cognitive mechanisms underlying aftereffects of tactile target and distractor processing. In order to dissociate the impact of distractor-specific processing and target-specific processing on subsequent performance, we employed a tactile variant of the sequential distractor repetition paradigm introduced by Giesen et al. (2012, Experiment 1). The results show both aftereffects of distractor processing as well as aftereffects of target-specific processing.

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[2] A closer look at the probe error data shows that the three-way interaction between response relation, distractor relation, and distractor set is mainly due to the comparably low amount of probe errors in the DCRR condition with neutral distractors. We assume that this condition is special in the tactile domain (see Craig, 1995), since tactile distractors interfere at two levels with responding to the target. On the one hand, they interfere at the perceptual level by adding noise or masking the target. On the other hand, they can be processed up to the level of response selection. In the DCRR condition with response-neutral distractors, the target profits from prime activation at both levels while the distractor just adds noise at the perceptual level. In the DCRR condition with response-incompatible distractors, additional response interference comes up that could oppose the prime-target activation. Thus, the three-way interaction in the probe error data reflects mainly how interference at the response selection stage impacts upon responding (and not differences in retrieval which should have been reflected in the RC trials as well).

(a)

(b)
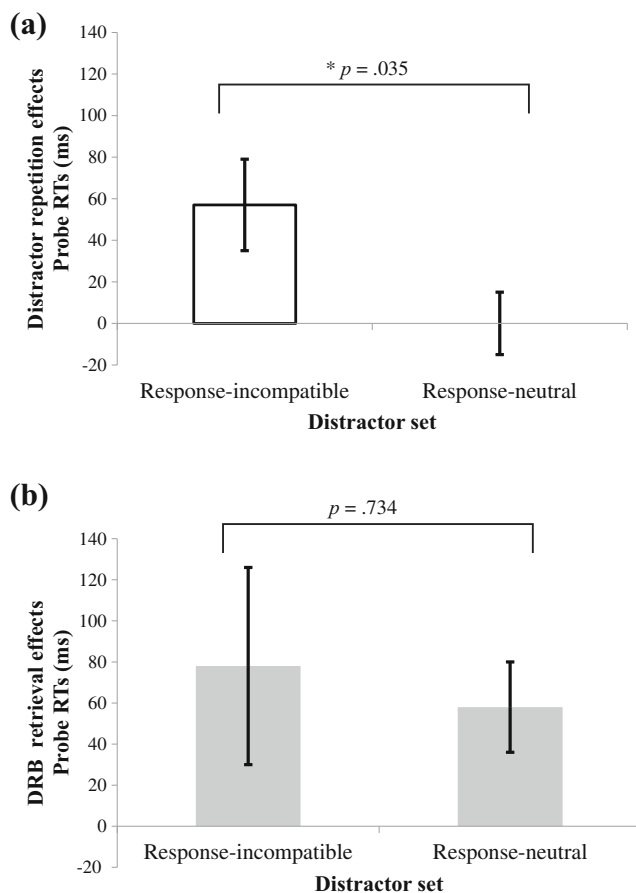
Fig. 3 **a** Simple distractor repetition (DRep) effects (probe trials with distractor change [DC] minus distractor repetition [DR], averaged across response relation; see Fig. 1a) for probe RTs. Positive values reflect probe performance benefits due to repeating a distractor from the prime trial. **b** Effects of episodic retrieval of distractor-response bindings (DRB retrieval effects; computed from Distractor Relation × Response Relation interaction effects in the probe trial: [DCRR − DRRR] − [DCRC − DRRC], see Fig. 1b) for probe RTs. Positive values indicate interaction effects that conform with expected effects due to distractor-based response retrieval (i.e., positive DRB retrieval effects for response repetition sequences and negative DRB retrieval effects for response change sequences). Error bars depict standard errors

Explaining aftereffects of distractor-specific processing in the tactile sensory modality

In particular, we found evidence for (a) distractor repetition advantages (reflected in a significant distractor-relation main effect) and (b) a modulation of this effect by distractor set, meaning that distractor-repetition effects were always stronger for response-incompatible compared with response-neutral distractors. Moreover, this pattern of effects emerged for both RTs and error rates in the present study, and therefore directly replicates the findings of Giesen et al. (2012), generalizing it to the domain of tactile distractor processing. In line with a large body of literature (e.g., Frings & Wühr, 2007; Lamy, Antebi, Avianti, & Carmel, 2008; Neumann & DeSchepper,

1991; Yashar & Lamy, 2010), one may interpret the main effect of distractor relation to reflect a benefit of distractor inhibition, persisting from the prime to the probe. Also, the Distractor Relation × Distractor Set interaction may be taken to support this interpretation, assuming that response-incompatible distractors impose stronger inhibition requirements on the individual performing a task than response-neutral distractors. As a result, it may be necessary to shield the response selection process against misspecifications (i.e., impede access to the associated response) only in the former condition, as response-neutral distractors are not associated with any (incorrect) response themselves.

Yet the main effect of distractor relation may also reflect retrieval effects. In detail, it may indicate classic distractor-induced episodic retrieval of a "do not respond" tag that must have been associated with the distractor during prime processing (see Neill & Valdes, 1992; Neill et al., 1992). Distractor repetition in the probe will elicit the retrieval of this "do not respond" tag, which will facilitate target selection, compared with distractor change probes. Regarding the Distractor Set × Distractor Relation interaction, it might then be assumed that only response-incompatible distractors are tagged with a "do not respond" tag, whereas neutral distractors are not. Note, however, that this is a somewhat speculative explanation that needs to be examined on an a priori basis in future studies. Taken together, based on the present data, we cannot disentangle whether distractor inhibition or episodic retrieval is more likely to account for the main effect of distractor repetition. However, our main interpretation of the data, which focuses on the dissociation of aftereffects resulting from target-specific and distractor-specific processing, is not affected by this question.

Explaining aftereffects of target-specific processing in the tactile sensory modality

The present study further showed significant effects of episodic retrieval due to incidental distractor-response bindings for tactile distractor stimuli that emerged as a by-product of target-specific processing during the prime trial (see also Moeller & Frings, 2011). For RTs, these effects emerged independently of whether tactile distractors interfered with response selection or not (i.e., independent from the manipulation of distractor set). For error rates, the pattern was somewhat different. In particular, we obtained a significant three-way interaction reflecting that DRB retrieval effects were significant for response-incompatible distractors but did not emerge for neutral distractors. At present, we can only speculate why that was the case (see also footnote 2). For instance, it is possible that response-neutral distractors received less attention (as a consequence of being "neutral" in the task). This would render them less effective retrieval cues (cf. Moeller & Frings, 2014), which accounts for the fact that only the time

course but not the outcome of response selection was biased by distractor-based response retrieval. More important in the present context, however, is that robust DRB effects emerged for response-incompatible tactile distractors, although the size of the elicited effects of distractor repetition differed between the distractor sets. These findings are consistent with the results of Giesen et al. (2012) and attest to the notion that distractor repetition effects and aftereffects of target-specific processing operate independently from each other, but also in concert in the service of efficient behavior regulation. Importantly, they can be empirically separated.

Limitations of the present study

In the current study, facilitation effects due to DRB retrieval were significant in response repetition sequences, whereas no significant impairment was observed due to DRB retrieval in response change trials. Still, this pattern of results is not uncommon in studies on DRB retrieval effects (e.g., Frings & Rothermund, 2011; Frings et al., 2007; Giesen, Eberhard, & Rothermund, 2015; Giesen, Weissmann, & Rothermund, 2018; Horner, 2016; Rothermund et al., 2005). Here, it is important to keep in mind that DRB retrieval effects are also influenced by other mechanisms that work independently of whether or not the response is repeated. One likely explanation is that the aftereffect of distractor processing enhanced facilitation due to DRB retrieval in response repetition, but diminished the impairment in response change trials. In the present study, distractor-based and target-based effects were roughly of the same size in response change sequences, leading to null effects. Note, however, that this is not always the case (e.g., Moeller et al., 2012). Instead the relation of the sizes of these effects likely depends on the specific stimuli used. Irrespective of these speculations, it is important to keep in mind that the only way to test for DRB effects is the interaction of response relation and distractor relation, which tests the *difference* between distractor repetition effects in response repetition and response change sequences. Notably, this interaction was always highly significant in the present result patterns.

In the current study, response repetition sequences correspond to target repetition sequences. Thus, DRB retrieval effects are obviously not the only target-specific effects influencing the present results. In particular, retrieval effects based on target-identity repetition might also play a role. However, several past studies have shown that DRB retrieval effects do not rely on target repetition trials. Rather, there is accumulating evidence that the retrieval of central elements of a previous episode can be purely distractor based (i.e., triggered by the repetition of an irrelevant stimulus or irrelevant stimulus feature; Giesen et al., 2012; see also Frings et al., 2007; Giesen & Rothermund, 2016; Moeller, Pfister, Kunde, & Frings, 2016b). In fact, a number of studies

support the conclusion that distractor- and target-based (or, more generally: feature-based) retrieval processes occur simultaneously, yielding additive, rather than multiplicative effects (see Hommel, 1998, 2007; Giesen & Rothermund, 2014, 2016; Moeller, Frings, & Pfister, 2016a). This implies that the evidence for DRB retrieval processes in the present study most likely reflects a compound of distractor-response and target-response bindings. However, we would like to point out that for the main point of our study, it is not necessary to separate processes of distractor-response and target-response binding/retrieval. The essential idea here is that binding and retrieval processes, elicited by target-specific processing during the prime episode, operate independently of distractor-specific processing during the prime trial, and that this holds true in the visual as well as tactile domain. Importantly, distractor-response and target-response retrieval effects were equally likely to occur for both distractor-set conditions. Thus, target-based retrieval processes cannot explain why simple distractor repetition effects were always stronger for interfering versus noninterfering distractors, whereas episodic DRB retrieval effects were insensitive to this manipulation.

Event file emergence and retrieval can be examined with the DRB task (as in the present study) or with other paradigms (e.g., the S1R1–S2R2 task, which has been used to analyze binding effects within the framework of the theory of event coding, cf. Hommel, 2004). Typically, the result pattern in the S1R1–S2R2 task reflects "partial repetition costs"—that is, impaired performance in partial repetition (i.e., only some features of the last episode are repeated) as compared with complete repetition and complete change trials (e.g., Zmigrod & Hommel, 2009), and thus differs slightly from the typical result pattern of the DRB task. In our view, the differences between the typical result patterns of both paradigms are most likely attributable to (a) the differences in the tasks and (b) the fact that DRB paradigms oftentimes include a response-incompatible distractor. Both of these paradigmatic differences lead to larger response repetition benefits and to a generally better performance in distractor repetition as compared with distractor change trials. Specifically, starting from a typical pattern of partial repetition costs, these two factors then lead to particularly faster DRRR (full repetition) trials, to still very fast DCRR (partial repetition) trials, and possibly somewhat faster DRRC (partial repetition) trials, while DCRC trials (full repetition) neither benefit from response repetition nor from distractor repetition.

In particular, one reason that response repetition benefits are typically larger in the DRB paradigm is that the task never changes between prime (R1) and probe (R2). Task-switching literature has shown that response repetitions compared with response changes produce performance benefits in task repetition sequences but lead to performance costs in sequences with task switches (e.g., Altmann, 2011; Druey, 2014; Hübner & Druey, 2006). This suggests that the slower response

repetition trials in the typical S1R1–S2R2 task are at least partly because the task switches between R1 and R2. Second, if response-incompatible distractors are included (as in our response-incompatible distractor-set condition), then specific distractor-related processes become relevant for performance in the DRB task, which are typically not necessary in a S1R1–S2R2 paradigm that presents only one response-relevant feature. If two response-relevant stimuli are presented at once and participants have to respond only to one of them, the other (distractor) stimulus needs to be somehow prevented from triggering a response. As we discussed earlier, this "somehow" may be a process of inhibiting the distractor, or an association of the distractor stimulus with a "do not respond" tag, or a combination of those processes. In any case, the result is an aftereffect of less distractor interference on probe target selection if the same distractor was already presented in the previous trial, resulting in a main effect of distractor relation. As we show in the present study, as well as in previous work (e.g., Giesen et al., 2012), these distractor repetition benefits are particularly pronounced for response-incompatible distractors, compared with response-neutral distractors (reflected in the Distractor Relation × Distractor Set interaction) and also occur independently of the DRB effects (the interaction of Response Relation × Distractor Relation), and does not further qualify it (indicated by the absence of a three-way interaction).

Conclusions and outlook

The present findings add to the literature on similarities between the senses of vision and touch regarding identity-based distractor processing (see also Frings et al., 2011). This is especially intriguing because the neurological underpinnings differ as a function of the sensory systems, not only because there are structures in the brain that are specifically involved in the information processing of only tactile/visual stimuli but also since the primary somatosensory cortex and visual cortex differ with regard to their organization (which is somatotopic in case of the somatosensory cortex, yet spatiotopic with regard to the external space in case of the visual cortex). Furthermore, while there is a distinction between "what" and "where" pathways for the visual system, this seems not to be reflected in the information processing of tactile stimuli (though see Reed, Grubb, & Steele, 2006, for a similar distinction). It is interesting that, despite these neural differences between the sensory systems, our behavioral data replicated the findings from the visual domain in a tactile task.

Notably, location-based information processing has recently also been investigated in different sensory modalities using the spatial NP paradigm. In this paradigm, participants respond to the location rather than the identity of a target stimulus (e.g., Tipper, Brehaut, & Driver, 1990). Remarkably, it seems that both tactile and visual spatial NP are location

specific rather than response specific (Neill & Kleinsmith, 2016; Wesslein et al., 2016; though see Buckolz, Goldfarb, & Khan, 2004). Whereas these findings highlight similarities between information processing in vision and touch in location-based tasks, the current study demonstrates similarities between the senses in a task focusing on identity-based information processing: In both sensory modalities, aftereffects of target-specific and distractor-specific processing can be disentangled. Taken together, this suggests that similar cognitive mechanisms may underlie tactile and visual information processing.

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