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Task-relevance and change detection in action-effect binding

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ABSTRACT

Features of actions are bound to coincidentally occurring stimuli so that re-encountering a stimulus retrieves a previous action episode. One hallmark of the purported mechanism in binding/retrieval tasks is a reliable reaction time advantage for repeating a previous response if tone stimuli repeat rather than alternate across trials. Other measures than reaction times yielded surprisingly mixed results, however. This is particularly true for continuous response features like force or response duration. We therefore conducted two experiments to resolve this disconnect between different measures. Experiment 1 tested for a potentially inflated effect in reaction time data, whereas Experiment 2 took the converse approach of studying conditions that would elicit similarly strong effects on alternative measures. Our results show that confounds in terms of auditory change detection do not inflate reaction time differences, reinforcing an interpretation of these effects as reflecting binding and retrieval. Moreover, strong effects on alternative measures appeared if these features were rendered task-relevant and came with sufficient variability. These observations provide critical evidence for binding and retrieval accounts, especially by showing that these accounts extend from binary decisions to continuous features of an actual motor response.

1. Introduction

In our daily lives, we perform various actions to manipulate our surroundings. We turn dials to adjust the temperature, push buttons to operate elevators, and increasingly, we use hand gestures to control virtual reality devices. While we typically aim at an ultimate goal, such as boiling water on an electric oven or reaching a certain floor in a building, achieving these goals depends on a series of successful intermediate steps that elicit different sensory action effects. These sensory effects seem to be irrelevant byproducts at first glance. However, closer inspection reveals that they inform about the success or failure of our actions (Horváth et al., 2018; Varga, Neszmélyi, et al., 2022), and they are even considered necessary components by which we represent these actions (Frings et al., 2020; Hommel, 2009, 2019). Indeed, recent views of action control suggest that action representations draw on such incidentally occurring sensory effects (whether external or internal, Pfister, 2019; Wirth et al., 2016) to initiate and control bodily movements.

Binding and retrieval is studied using a variety of experimental paradigms, such as negative priming, task-switching and repetition priming tasks (see Frings et al., 2020 for a summary) that often have a similar sequential structure, consisting of a prime and a probe trial. One way to assess binding and retrieval is to have actions produce certain stimuli (i.e. effects) in a prime trial, and assess the type and performance of responses to stimuli in a subsequent probe trial which either repeat the prime stimulus (i.e. are congruent) or change (i.e. are incongruent). Retrieval of a response previously bound to a stimulus is assumed when the response to a repeating stimulus is more similar (e.g., in terms of identity, force or duration) and produced more quickly (in terms of response times) when the stimulus in the probe trial repeats rather than changes (e.g. Dutzi & Hommel, 2009; Herwig & Waszak, 2012; Varga, Pfister, et al., 2022). The assumption behind this is that a re-encountered stimulus in the probe trial retrieves the response to which it had been bound in the prime trial, while all other processes remain unaltered. However, this may not necessarily be the case, as a stimulus (e.g. sound) repetition and a stimulus change may itself exert an influence on

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behavioural parameters that may lead to spurious signs of binding and retrieval.

One potential confound due to stimulus sequences is that changing a stimulus may signal participants to change their behaviour. This simple decision-making heuristic could appear as a tendency for participants to code a stimulus as the repetition or alternation of a previously presented stimulus, leading to a simple strategy: if the stimulus repeats, repeat the response. If it changes, change the response. The signalling hypothesis holds that changing a stimulus renders successive actions *dis*similar (e.g., in terms of identity, force or duration) as compared to repeating a stimulus (Weissman et al., 2023). For typical experimental setups with just two response options (e.g., a left and right key), this decision heuristic predicts the same data pattern as binding and retrieval accounts without assuming any binding to take place. Evidence from more complex experimental setups indicates that binding and signalling both contribute to the data pattern that is usually taken to indicate binding and retrieval (Weissman et al., 2023). However, signalling is not the only potential confound of comparing stimulus sequences with repeating versus changing stimuli. Evidence indicates that repeating a stimulus affects how this stimulus is processed by the sensory system, which may also affect behavioural performance.

When a sound stimulus repeats within a short interval, neural reflections of its sensory processing are reduced (for a summary, see Näätänen & Picton, 1987), partially due to the repetition of stimulus features (e.g. Herrmann et al., 2013; Mäkelä et al., 1987; Näätänen et al., 1988). This suggests that the second sound in congruent and incongruent sound pairs are processed differently: a sound change (i.e., incongruent trials) results in amplified sensory processing, which may give rise to differences in arousal, may elicit an involuntary attentional change, and thus may also increase reaction times in discrimination tasks (Rinne et al., 2006; Schröger, 1996). Recent studies also show that sounds that typically activate auditory change detection systems may disrupt the programming or maintenance of response plans (e.g. sounds presented after longer periods of silence - Novembre et al., 2018; infrequently presented spectrally rich, novel sounds - Parmentier & Gallego, 2020). Therefore, it seems plausible that similar effects may arise when reacting to changing (as opposed to repeating) stimuli. Thus, the goal of Experiment 1 was to investigate this alternative explanation, a potential confound that would result in the same experimental effect as binding and retrieval.

Returning to the commonalities between binding and retrieval paradigms (as well as turning to Experiment 2), we can see a general focus on action properties that are task-relevant and categorical in nature (e.g., decision categories such as responding "left" vs. "right"). Recent research aims to extend findings to continuous features. For example, in Beyvers et al.' (2022) experiment, participants reached out, grasped and lifted up an object, then placed it back and returned their fingers to the starting position, all within five seconds. When performing two such actions in sequence, changing the mass distribution of the object had a profound impact on kinematic parameters such as the tilt angle of a manipulated object. This suggests that participants planned a similar movement upon repeated exposure to the same object, which is consistent with the idea of binding and retrieval of continuous features relating to actual motor execution.

Other approaches to binding and retrieval of continuous features did not warrant strong conclusions. In Varga, Pfister, et al. (2022), participants had to produce pinches in a prime trial, thus producing a high- or low-pitched tone. In the subsequent probe, the previously presented tone was repeated (congruent trials) or a different tone was presented (incongruent trials), which required a fast pinch reaction. We compared the force, duration and reaction time (RT) for the action in congruent and incongruent trials and found mixed results (for additional background on response durations, see Pfister et al., 2023). Actions tended to be more similar to each other in congruent than in incongruent trials, as well as being initiated faster, but these differences were much smaller in effect size than what is commonly found in the literature, with several tests not showing evidence for binding and retrieval at all. In discussing these results, we highlighted some particularities that could help explain our findings. One consideration is task relevance. Participants performed the task with only a single interaction option being available (as opposed to choice response tasks that are commonly used to study binding and retrieval; Frings et al., 2020), and these interactions' properties were not relevant to the task. That is, action force and action duration were freely chosen in each case. We speculated that perhaps task-irrelevant action features are not retrieved to the same extent as task-relevant properties. A different, but related consideration is the variability of these action features. Because participants could freely choose the executed pinch's force and duration (perhaps settling for a force level that was less effortful while still maintaining a high probability of action success, Neszmélyi & Horváth, 2017), there was no incentive to vary it from trial to trial, hence the overall variability could have been low. A simple modification of the task, requiring both weak and forceful actions on the prime, allows for both an increase in variability, as well as modifying the task relevance of action force. This modification was implemented as the current Experiment 2.

Taken together, we had two primary goals in this study: in Experiment 1, we investigated an alternative explanation to results typically interpreted as reflecting binding and retrieval, namely, whether the repetition/change of auditory stimuli between a prime and probe trial per se leads to reaction time and possibly other differences in force exertion. In Experiment 2, we tested whether the binding and retrieval effect for simple actions can be amplified by making action force task-relevant on the prime, as well as increasing its overall variability.

2. Experiment 1

Experiment 1 in Varga, Pfister, et al. (2022) followed the experimental design of Moeller et al. (2016) for the investigation of action-effect, more precisely action-sound, bindings. Results in that study showed that responses in congruent probes were initiated faster than responses in incongruent probes. Some evidence was found for higher variability in the duration of force application as well, with the correlations between prime and probe action durations being higher in congruent than in incongruent trials (see Experiment 1 and the Pooled analyses in Varga, Pfister, et al., 2022). In Experiment 1 we tested the hypothesis that sound change per se might have resulted in delayed responses and increased variability in action durations compared to sound repetition. To test this hypothesis, we repeated Experiment 1 from the study by Varga, Pfister, et al. (2022) and included a control condition in which a simple reaction was required to the second tone of a pair of repeating or alternating auditory stimuli. We hypothesized that if binding and retrieval truly contribute to the congruency effect, then the reaction time difference between congruent and incongruent trials would be larger in the experimental than in the control condition, that is, a condition × congruency interaction would emerge.

2.1. Method

2.1.1. Participants

In our previous experiments (Varga, Pfister, et al., 2022) our smallest effect size was $d_z = 0.39$ (for the AUC correlation comparison), while the reaction time difference was of $d_z = 0.48$ magnitude. To target a similar effect size of $d = 0.4$ with 1-β = 0.80 and $\alpha = 0.05$, we recruited 51 participants. Our sample consisted of predominantly right-handed (2 participants were left-handed) young adults ($M = 22$, $SD = 2.7$, range = 18–30), out of which 35 participants were women and 16 were men.

2.1.2. Materials, stimuli and data acquisition

The location, devices and setup used were very similar to Experiment 1 in Varga, Pfister, et al. (2022). We used a single-zone force sensitive resistor (FSR 400, Interlink Electronics, Westlake Village, CA, USA; 0.3 mm thick, active area of 5.1 mm diameter) that was mounted on a thin plastic sheet. This device was then glued to the surface of a table. During the experiment, participants rested their dominant hand palm down on the table and put their index finger on the device, maintaining contact throughout the blocks. As actions and reactions, they applied brief force impulses on, that is, pressed the device. The FSR signal was recorded with a voltage-divider setup using the high-level input of a SynAmps2 EEG amplifier (Compumedics Neuroscan, Victoria, Australia) with 24 bits resolution, 1000 Hz sampling rate, and a 200 Hz online lowpass filter. The FSR signal was transformed into force by an exponential transformation. An action was registered if the signal exceeded the preset threshold of 0.52 N after being under the threshold for at least 60 ms.

Auditory stimuli were 300 ms long (including 10–10 ms linear rise and fall times), 60 dB(SPL), 440 and 1175 Hz pure tones presented via headphones (Sennheiser HD-600, Wedemark, Germany). Because of hardware constraints, there was a constant 6 ms delay in the presentation of the tones in relation to the detected action onsets. Instructions and feedback were presented on a 24-in., 1920 × 1080 pixels resolution liquid crystal display (BenQ XL2430) placed approximately 1 m in front of the participant. The experiment was run by custom scripts in GNU Octave (Eaton et al., 2014) using the Psychophysics Toolbox (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997) on a Linux operating system.

2.1.3. Task and procedure

During the experiment, participants sat in an armchair in a sound-attenuated room. First, the experimenter demonstrated the proper finger placement and usage of the FSR and instructed the participants to operate the device themselves. During this phase, FSR signals were continuously displayed on a separate monitor, so participants could see the difference between strong and weak force impulses. After being familiarized with the device, the separate monitor was turned off, and the experiment started with the first condition (experimental or control, randomized between participants). Each condition started with a practice block followed by 5 experimental blocks. Each block started with instructions appearing on the main screen.

The experimental blocks' instructions were: 'Your task will be to wait for 2 seconds, then press the device. The button press will be followed by a sound, and sometimes by a second one as well. If you hear a second sound, quickly press the device! Let us know when you are ready to begin!' In the control blocks, the instructions were slightly modified: 'Your task will be to wait until you hear a sound. In some of the trials, two sounds will be presented. If you hear a second sound, quickly press the device! Let us know when you are ready to begin!'If participants asked questions, the instructions were clarified, and when ready, participants worked through one practice block containing 20 trials (8 congruent and 8 incongruent trials and 4 no-go trials – the number of congruent, incongruent and no-go trials was the same for both conditions). Maintaining the 20 % ratio of no-go trials, experimental blocks comprised 16 congruent, 16 incongruent and 8 no-go trials, amounting to 200 trials in each condition (excluding practice blocks). The duration of the experiment was ca. 40 min plus breaks.

Fig. 1 depicts the trial structure in Experiment 1. In the experimental blocks, trials started with a minimum wait time of 2 s, after which participants pressed the device. In control blocks, the wait time varied randomly between 2 and 3 s (sampled from a uniform distribution). For the two types of blocks, two different texts appeared on the screen (*'Wait for 2 s, then press'* – experimental blocks; *'Wait for the second tone, then press'* – control blocks), that remained displayed during the trial, unless an error occurred (see below). These texts, as well as previous instructions, were presented using black font on a white background. After the initial wait time, participants pressed the device, thus producing a high or low tone (experimental blocks), or a (high or low) tone was presented (control blocks). The tone was either followed by a second tone of the same (congruent trials) or different pitch (incongruent trials) with a 600 ms onset-to-onset interval, or no second tone was presented (no-go trials). In trials where a second tone was presented, participants quickly pressed the device, thus ending the trial. The subsequent trial started after an intertrial wait time of 1 s. There were four possible deviations from this procedure. In the experimental condition, if participants did not wait for at least 2 s before initiating the first press, a warning appeared on the screen (*'Too fast! Wait for 2 seconds!'*) and the trial was restarted (repeated). If participants pressed within 600 ms following the first tone (i.e. before the potential onset of the second

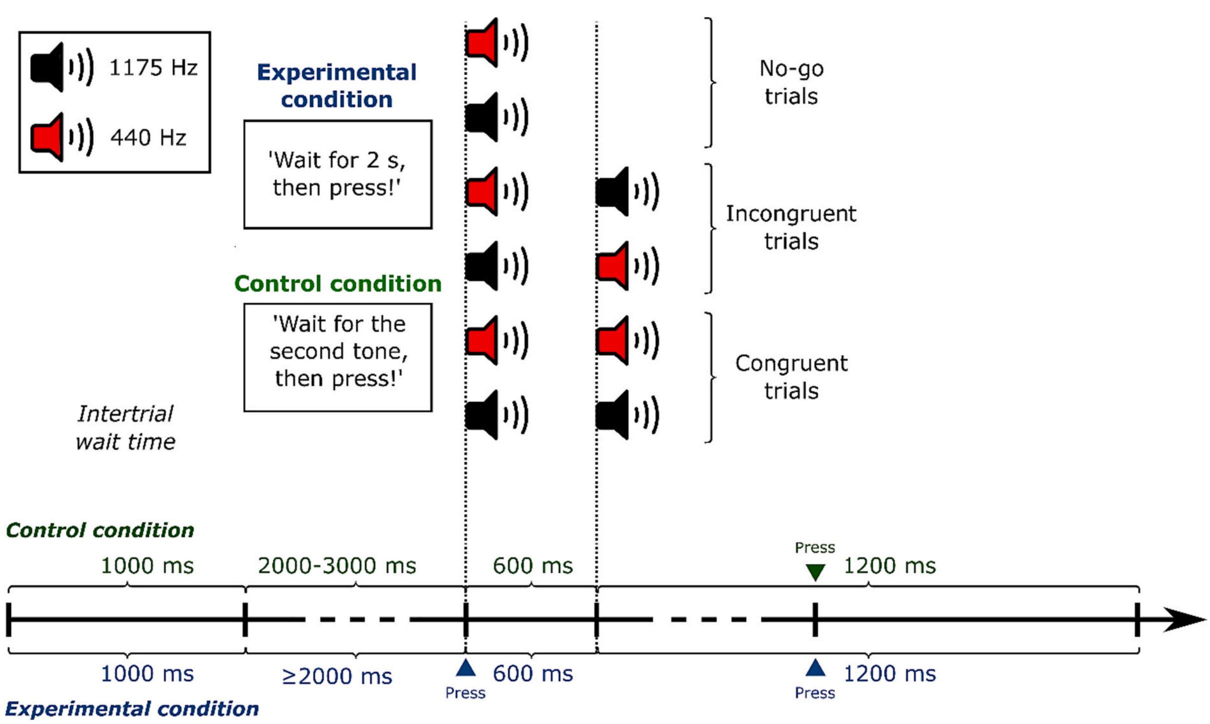

Fig. 1. Trial structure in Experiment 1. Stimulation and action timing for the Control and Experimental conditions are presented respectively above and below the horizontal time axis at the bottom.

tone), a different warning appeared *('Wait for the tone, please!')*, the trial ended and the action was registered as a false alarm. If participants pressed the device on no-go trials, the same warning was presented *('Wait for the tone, please!')*, the error was registered and the trial ended. All warnings were presented for 1 s, using red font and white background. Finally, if participants did not press the device within 1200 ms after the onset of the second tone, the trial was registered as a missed event. At the end of each block, a feedback message displayed the number of false alarms and the number of missed events.

2.1.4. Data selection and analyses

For the experimental condition, we rejected trials with reaction times shorter than 100 ms ($M = 1.14$ [0.71 % of go trials], $SD = 2.40$ [1.50 %], range = 0–15 [0.00–9.38 %]; computed per participant, condition and congruency), and trials with (late) response times 2.5 standard deviations above the mean ($M = 3.82$ [2.39 %], $SD = 1.45$ [0.91 %], range = 0–7 [0.00–4.38 %]). Trials in which force application did not end within 600 ms after the prime or probe were also rejected (thus ensuring that force application was finished by the time the probe was presented): $M = 3.45$ (2.16 % of go trials), $SD = 11.06$ (6.92 %), range = 0–58 (0.00–36.25 %).

The number of rejected trials was similarly low for the control condition: the average number of trials with reaction times shorter than 100 ms was 0.69 (0.43 % of go trials], $SD = 1.57$ [0.98 %], range = 0–9 [0.00–5.63 %], and the average number of trials with (late) response times 2.5 standard deviations above the mean was 2.92 ([1.83 % of go trials], $SD = 1.67$ [1.04 %], range = 0–7 [0.00–4.38 %]). To maintain processing similarity between conditions, trials with press durations longer than 600 ms were also discarded in the control condition. This constituted 7 trials in total ($M = 0.14$ [0.09 % of go trials], $SD = 0.53$ [0.33 %], range = 0–3 [0.00–1.88 %]).

Data points that were lower or higher than the mean by 2.5 standard deviations were also rejected for each measured dependent variable (force and duration), computed separately for each participant, condition and congruency.

Force application was characterized by the temporal integral of force (area under the curve – *AUC*). For the AUC calculation, the action onset was determined as the time point when the signal exceeded the predefined threshold of 0.52 N after an under-threshold period of at least 60 ms. Action offset was registered when the signal dropped below, and remained under the threshold for at least 10 ms.

Reaction times were analyzed in a 2 × 2 repeated-measures ANOVA, with condition (experimental/control) and congruency (tone repetition/alternation) as factors. As a complementary analysis for the experimental condition, intraindividual Pearson-correlations between prime and probe-related force applications were compared by Student's paired *t*-test for congruent and incongruent trials. The same type of comparison was also conducted for action duration. To ensure an approximately normal distribution of sample correlations, *r* coefficients were Fisher's *Z*-transformed before the comparisons (Fisher, 1921).

2.2. Results

2.2.1. Error rates and misses

In the experimental condition, the average number of missed trials per participant was 0.55 ($SD = 1.64$, range = 0–10), corresponding to 0.34 % ($SD = 1.03$, range = 0.00–6.25 %) of the trials (excluding no-go trials). The number of misses was similarly low in the control condition, averaging 0.39 trials ($SD = 1.23$, range = 0–6) per participant (percentage of trials: $M = 0.25$ %, $SD = 0.77$ %, range = 0.00–3.75 %). There were on average 1.26 no-go trial errors ($SD = 1.81$, range = 0–9), accounting for 3.14 % of no-go trials ($SD = 4.52$ %, range = 0.00–22.5 %) in the experimental condition, and 0.80 in the control condition ($SD = 1.70$, range = 0–10), which constitutes 2.05 % of no-go trials ($SD = 4.25$ %, range = 0.00–25.00 %). The number of presses within 600 ms of prime onset (i.e. before the potential probe onset) was again low both in the experimental condition: 0.49 ($SD = 0.99$, range = 0–5), representing 0.24 % of all trials ($SD = 0.49$ %, range = 0.00–2.49 %); and the control condition:0.51 ($SD = 0.81$, range = 0–3), 0.26 % of all trials ($SD = 0.41$ %, range = 0.00–1.50 %).

2.2.2. Reaction time analysis

The 2 × 2 repeated-measures ANOVA (Fig. 2.) showed a significant congruency main effect ($F_{(1,50)} = 4.79$, $p = .033$, $\eta^2_G = 0.001$), a significant condition main effect ($F_{(1,50)} = 23.29$, $p < .001$, $\eta^2_G = 0.036$), and most importantly, a significant interaction ($F_{(1,50)} = 29.49$, $p < .001$, $\eta^2_G = 0.002$, $d_z = -0.76$), showing that the congruent-minus-incongruent reaction time difference was larger in the experimental ($M = -18.35$ ms, $SD = 26.65$ ms) than in the control condition ($M = 2.87$ ms, $SD = 30.88$ ms). The reaction time difference between congruent and incongruent trials was not significant in the control condition ($t_{(50)} = -0.67$, $p = .51$, $d_z = -0.09$).

2.2.3. Force and action duration analyses in the experimental condition

Pearson's correlations between prime and probe force (AUC) calculated for each participant were submitted to Fisher's *Z*-transformation. The transformed correlations did not significantly differ ($t_{(50)} = 1.57$, $p = .122$, $d_z = 0.22$) between congruent ($M = 0.60$, $SD = 0.31$) and incongruent trials ($M = 0.56$, $SD = 0.30$).

The same type of analysis for action durations showed no significant difference ($t_{(50)} = 0.62$, $p = .541$, $d_z = 0.09$) between congruent ($M = 0.50$, $SD = 0.24$) and incongruent trials ($M = 0.49$, $SD = 0.24$).

2.3. Discussion

The reaction time results of Experiment 1 clearly show that increased response time in trials with tone changes (i.e. incongruent trials) in comparison to trials with tone repetitions (i.e. congruent trials) is not caused by the auditory change on its own. An RT effect only appears when the presented stimulus was previously associated with an action on the prime and its repetition on the probe facilitates the following action. This result supports the claim that RT differences in this paradigm are better explained by binding and retrieval. If anything, response times in the control condition were somewhat higher in congruent than in incongruent trials, although this difference was not statistically significant. We speculate that this might reflect the binding of tones to a 'no-go'-tag, as in control condition trials responses to the first encountered tone were not allowed (Giesen & Rothermund, 2014). Note, this interpretation rests on the assumption that the binding of sound to response features had occurred in the prime trial (Weissman et al., 2023). Force and action duration analyses for the experimental condition did not result in significant differences, even though actions in congruent trials were descriptively more similar to each other than actions in incongruent trials. Because half of the participants started with the control condition, the experiment was presented as a reaction time task, with the emphasis being on quick responses. As we discuss later, this shift of importance on some aspects of the task might help explain why, under different conditions, measures differ in the ability to capture binding and retrieval effects.

3. Experiment 2

The force analysis of Experiment 1 as well as the results presented in Varga, Pfister, et al. (2022) raise the question of what could explain the inconsistency of the binding and retrieval effect when it comes to action force (and duration) relative to common tests that employ RT and error rates. Varga, Pfister, et al. (2022) suggested two potential explanations: 1) perhaps retrieval depends on task-relevancy: task-irrelevant action properties may not be retrieved to the same extent as task-relevant features or 2) the overall variability of actions might be too low. To investigate these explanations, we modified our paradigm by making action force task-relevant on the prime while also increasing its

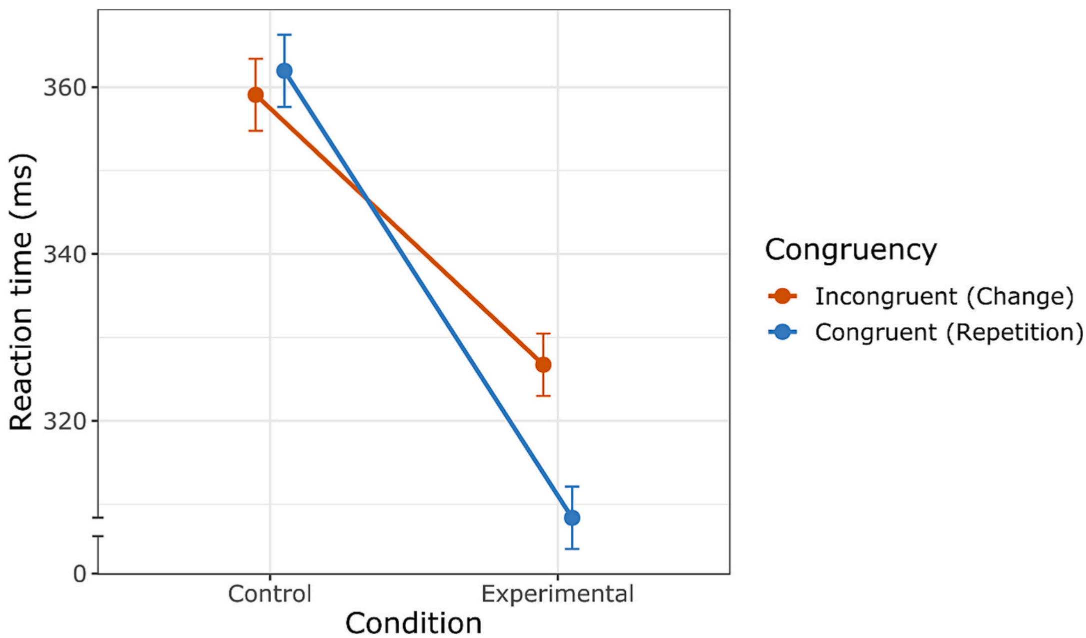

Fig. 2. Mean reaction times in Experiment 1. Error bars depict the standard error of paired differences for each comparison (congruent-incongruent trials).

variability. We asked participants to spontaneously carry out weak and strong actions on the prime while maintaining a roughly equal ratio of weak and strong actions. As before, action force on the probe was irrelevant, the only requirement was to respond fast on go trials. Because the procedure was similar to Experiment 1, in the following, we only describe the relevant differences in Experiment 2.

3.1. *Method*

3.1.1. *Participants*

As in Experiment 1, we aimed for at least 51 participants to be able to detect an effect size of $d = 0.4$ with 1-$\beta = 0.80$ and $\alpha = 0.05$. We recruited 63 participants to make sure that the target participant number is met even if data needed to be rejected later. In total, seven datasets were rejected (see below for details). Participants were predominantly right-handed (1 participant was left-handed) young adults ($M = 22$, $SD = 6.2$, range = 18–46), out of which 52 participants were women and 11 were men.

3.1.2. *Materials, stimuli and data acquisition*

During the experiment, participants sat in a chair at a table, with the experimenter sitting behind them at a distance of 2 m. The positioning and the operation of the device were the same as in Experiment 1. The signal of the FSR (FSR06CE, Ohmite, Warrenville, IL, USA; 0.375 mm thick, circular active area with a diameter of 14.70 mm) was recorded with a sampling rate of 1006 Hz, at 14 bits resolution by a Teensy 3.2 development board with an Audio Shield (PJRC.COM, Sherwood, OR, USA). Raw values were converted to force using an exponential transformation. Auditory stimuli were delivered by the Audio Shield through headphones (Sennheiser HD-25, Wedemark, Germany) with an intensity of 68 dB (SPL). For congruent and incongruent trials, 440 and 1175 Hz, 150 ms long (with 10–10 ms linear rise and fall times) tones were used. Instead of the absence of a tone, on the no-go trials, a distinct complex noise (referred to as "clanging sound") was presented that was 150 ms long with 10 ms rise and fall ramps, with a dominant spectral peak at around 1080 Hz. The use of a third tone rather than the absence of a probe tone to indicate no-go trials intended to encourage participants to pay attention to the identity of the probe stimulus rather than simply noticing the change.

3.1.3. *Task and procedure*

As in Experiment 1, the task started with a familiarization phase. Participants were asked to carry out 8 brief presses with the index finger of their dominant hand, without raising their finger between two actions. After performing these actions, a figure was presented on the computer screen, showing the temporal development of force application in the −100 to 500 ms interval around each action onset. Participants were encouraged to keep presses brief, with the applied force returning to the baseline within 400 ms. When necessary, this phase was repeated.

The second phase was a triplet of blocks in which participants were instructed to perform specific patterns of actions. The first block required 8 strong presses. After performing these presses, a figure showing the temporal development of force application for all 8 presses, as well as a red horizontal line marking the half maximum force for the press with the highest force peak was shown. The same red line was drawn on each action's force curve. Participants were informed that this line represented their individual cut-off point that would separate strong and weak presses, with strong presses reaching force levels above the red line and weak presses staying under it. The second and third blocks of the triplet required a specific alternation of weak and strong actions (*swswswsw* and *wwsswssw*, with s = strong action, w = weak action). After each block, the experimenter inspected the figures, and when necessary, encouraged participants to maintain the required force levels and briefness of presses.

After completing this phase, participants worked through a practice block that was identical to the experimental blocks, containing 12 congruent trials (tone repetition), 12 incongruent trials (tone alternation) and 6 no-go trials (with a noise appearing on the probe). The practice block and the following experimental blocks started with the following instructions appearing on the screen: *'Your task will be to wait at least two seconds, then press the force-sensitive device. The press should be randomly weak or strong! Try to press softly and forcefully about equally as often, but do this spontaneously, without planning! The press will always be followed by two tones. The second tone can be of three types: If the tone you are hearing is not the clanging sound, press the device as fast as possible. If, however, what you hear is a clanging sound, do not press the device! The forcefulness of the second press does not matter. Let us know, if we can begin!*'Each trial started with a requirement to wait at least two seconds, after which participants had to spontaneously press the FSR either weakly or forcefully. This action elicited a high- or low-pitched tone that was followed shortly by another one, requiring either a simple reaction with a freely chosen strength (in congruent and incongruent trials) or no further actions (no-go trials). At the end of each block (both practice and experimental), a figure showing the temporal development of force application for all prime-related presses was shown, in the format described above, with the red line marking the half-maximum force. The experimenter and the participant inspected the force curves, and when necessary, the experimenter encouraged the participant to keep up a similar distribution of weak and strong presses. The practice block was followed by 7 experimental blocks containing 30 trials each. Fig. 3 presents the trial procedure in Experiment 2. Warning texts were similar to Experiment 1, but presented as black text on a red background. While premature presses on the prime elicited the same warning, false alarms were signalled as: *'Wait for the second tone!'* For no-go errors, the following text was displayed: *'Do not press the device for this sound!'*.

3.1.4. Data selection and analyses

We rejected trials with reaction times lower than 100 ms (M = 2.4 [1.43 % of go trials], SD = 5.4 [3.21 %], range = 0–31 [0–18.45 %]) and trials with (late) responses 2.5 standard deviations above the mean (M = 3.4 [2.02 %], SD = 1.7 [1.01 %], range = 0–8 [0–4.76 %]). We further filtered the data for each analysis and measure (separately for each participant and congruency), discarding data points below and above z = 2.5.

For the analyses, we calculated the 1) intraindividual correlation of prime and probe force across trials between tone repetitions/changes (measured in terms of AUC, with the threshold of 0.54 N marking the beginning and the end of an action), 2) the intraindividual correlation of prime and probe duration across trials between tone repetitions/changes and 3) reaction times on the probe for congruent and incongruent trials.

3.2. Results

In general, participants found it difficult to maintain the desired ratio of forceful and weak presses on the prime, with strong presses being weaker than intended (see Fig. S1 in the Supplementary Material; this was even communicated by some participants).

3.2.1. Error rates and misses

The occurrence of trial restarts (i.e. when participants waited for less than 2 s before the first action) showed substantial individual differences (M = 23.2 [11.05 % of all trials], SD = 17.6 [8.38 %], range = 1–85 [0.48–40.48 %]), along with the number of errors on the no-go trials (M = 4.1 [9.76 % of no-go trials], SD = 5.0 [11.91 %], range = 0–27 [0–64.29 %]). We rejected datasets from participants with error rates ≥ 33 % (four participants). Most participants had only a few missed trials (no action on the probe, M = 5.2 [3.17 % of go trials], SD = 9.1 [5.42 %], range = 0–56 [0–33.33 %]), but one subject did not have a second action in 56 trials, suggesting a misunderstanding of the procedure, hence this participant's data was discarded from further analyses. A different participant's first 4 blocks were discarded for the same reason, thus leaving a total of four blocks for the analyses. Furthermore, upon inspection of the data, we found that two participants displayed a particular strategy, with weak actions on the prime being followed by strong actions on the probe or vice versa, hence their data were excluded. Finally, there were on average 5.1 trials [2.43 % of all trials], where participants pressed before the arrival of the second tone (SD = 5.2 [2.48 %], range = 0–31 [0–14.76 %]).

3.2.2. Reaction time analysis

Mean reaction times did not show a significant difference when comparing congruent (M = 379 ms, SD = 108 ms) and incongruent (M = 381 ms, SD = 101 ms, $t_{(53)} = 0.70$, p = .49, $d_z = 0.10$) trials.

3.2.3. Force and action duration analyses

The Fisher's Z-transformed correlations between prime and probe force (AUC, see Fig. 4A) showed a statistically significant effect, with actions in congruent trials (M = 0.46, SD = 0.37) being more similar to each other when compared to incongruent trials (M = 0.39, SD = 0.33, $t_{(53)} = 3.14$, p = .003, $d_z = 0.43$). The transformed correlations were significantly different from 0 both in congruent ($t_{(53)} = 9.23$, $p < .001$, $d_z = 1.26$) and incongruent trials ($t_{(53)} = 8.58$, $p < .001$, $d_z = 1.17$).

Similarly, the transformed correlation coefficients of action duration (Fig. 4B) were higher in the case of congruent trials (M = 0.44, SD = 0.35) than incongruent trials (M = 0.32, SD = 0.35, $t_{(53)} = 4.80$, $p < .001$, $d_z = 0.65$). The transformed correlations were significantly different from 0 both in congruent ($t_{(53)} = 9.17$, $p < .001$, $d_z = 1.25$) and incongruent trials ($t_{(53)} = 6.73$, $p < .001$, $d_z = 0.92$).

3.3. Discussion

In Experiment 2, actions eliciting the prime and responses to the following probe were more similar to each other in exerted force and duration when the probe was a repetition of the prime tone compared to when the tone changed. This, in light of the results of Experiment 1, can be interpreted as a demonstration that the repetition of a stimulus that was previously coupled with an action retrieves associated features, in this case, action features such as force and duration. This seems to be more apparent when these features are task-relevant, as opposed to being task-irrelevant (as in Experiment 1 and Varga, Pfister, et al., 2022). While in this experiment, the task relevance of force in particular was increased by asking participants to actively vary it on the prime, the effect manifests itself in action duration as well, as actions that tend to be more forceful are also generally longer (correlation between action duration and AUC of all actions on the prime: r = 0.63 and probe: r = 0.69 in Experiment 2; see also Horváth et al., 2018). This is not the case for reaction times (correlation between RT and action duration on the probe: r = 0.04), with our results presenting further evidence that response times and action duration are not correlated (Pfister et al., 2023). Indeed, the reaction time comparison of the actions in congruent and incongruent trials serves as indirect evidence for the importance of the task itself. Compared to Experiment 1, there was no RT difference between congruent and incongruent trials. We speculate that the added difficulty of being asked to be spontaneous on the prime and maintain a 1:1 ratio of weak and strong actions (as evidenced by participants' difficulty in adhering to the desired ratio, see Supplementary Material) might have resulted in a shift of emphasis from the probe to the prime. Indeed, the reaction times (both in congruent and incongruent trials) were the slowest that we have found in our experiments using this paradigm (Experiment 1 and Varga, Pfister, et al., 2022). Long reaction times might also reflect a sequential difficulty effect, that is, impaired performance after a difficult trial (Schneider & Anderson, 2010).

As a related point, although in this experiment the exact distribution of weak and strong presses is not really important (its main purpose being the increase in variability and making force task-relevant), many participants' apparent failure to reach the predefined threshold does contribute to the argument that we do not really have precise, conscious control over action force in ballistic movements (de Graaf et al., 2004; Hommel, 2013). The difference in performance in this area is also reflected in the fact that within-subject variability of forces is smaller than between-subject variability. This might reflect slow fluctuations in action readiness and a difference in tendency (or ability) to repeat an action with- or without small changes in finger placement (see supplementary figs. S2, S3 and S4 illustrating the difference in actions of three representative participants).

4. General discussion

The two experiments suggest that task relevance plays a profound role in binding and retrieval, whereas (auditory) change detection does

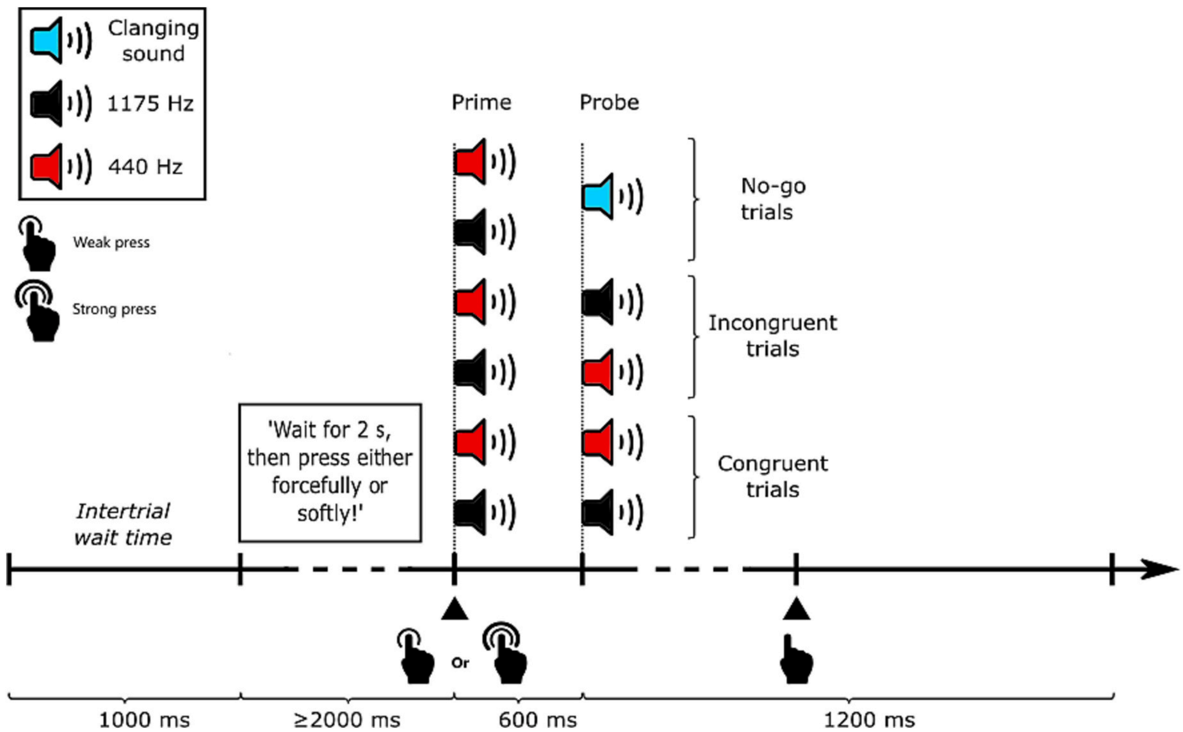

Fig. 3. Trial structure in Experiment 2. On the prime, the required action was a spontaneous weak or forceful press. Conversely, on the probe, action force was freely chosen.

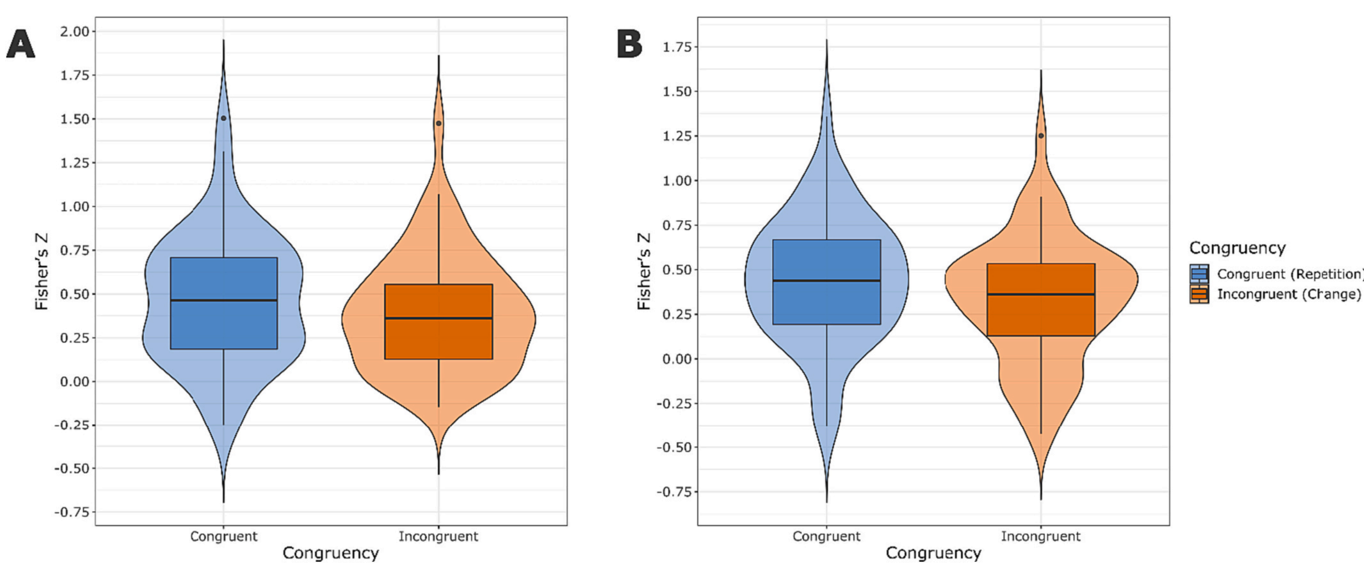

Fig. 4. (A) Fisher's Z-transformed correlations between prime and probe force (AUC). (B) Fisher's Z-transformed correlations between prime and probe duration.

not. Against this background, the concept of task-relevant and task-irrelevant action features warrants further elaboration. Whereas in Experiment 1 and in Varga, Pfister, et al. (2022), the studied action features, force and duration, were task-irrelevant because no specific instruction regarding patterns in force or action duration was given, in Experiment 2, an instruction regarding the pattern of force application with separable force categories was introduced. Because the instruction emphasized the relevance of force on the prime, but its irrelevance on the probe, one may suggest that the instruction was not a manipulation of the retrieval of action features but rather that of their binding. Task relevance thus seems to appear as a key factor influencing binding (and not retrieval) of continuous properties of simple actions. This is not necessarily the case, however. Binding is considered to be a largely automatic, spontaneous, and rather non-selective process (Kiesel et al., 2023) that integrates relevant as well as irrelevant elements, such as distractors (e.g. Frings et al., 2007; Schmalbrock et al., 2023). In contrast, retrieval is the more selective process, with attention being an important factor that determines what gets retrieved (Hommel et al., 2014; Moeller & Frings, 2014). In Varga, Pfister, et al. (2022) and in Experiment 1 of this study, force was task-irrelevant and it varied in a narrow range, while in Experiment 2, the increase in variability was reached by making force task-relevant on the prime. Thus, in these experiments, task-relevance and action variability are coupled. This leads to the suggestion that in Experiment 2, the task-relevance of force might not affect binding and retrieval directly, but rather indirectly by increasing the variability of actions. Future research could aim to disentangle these aspects.

A different question that might be an interesting topic for future exploration is related to the results of Experiment 1. There was a significant interaction between condition and congruency measured in reaction times of actions. We interpret this result as evidence for the presence of binding and retrieval. Interestingly, there was also a significant main effect of condition, with reactions in the experimental condition being faster than reactions in the control condition. One could speculate that perhaps the presence of the sound itself as an action effect might facilitate reaction times in the experimental condition, even in incongruent trials. The two tones used, while differing in pitch, were of the same duration and sound pressure level. It might be the case that having some shared similarities with a different tone (a tone that was bound together with features of a previous action) still provides some benefits of retrieval, although not to the same extent as the actual tone that was presented (i.e. congruent trials). The obvious difference is, that in the experimental condition, there is an action on the prime as well, whereas there is none in the control condition, and having a single interaction option, the required response never changes. Thus the between-condition effect might also be the result of simple action repetition.

This latter point concerning action repetition may bring up an alternative explanation to the results described in this study. Because in this paradigm the required action always repeats (in contrast to paradigms that use two response options, such as left- and right-handed button presses), one could speculate that the results described might reflect a form of strategy: 'if the stimulus (S) repeats, repeat the response (R); if the stimulus (S) changes, change the response (R)'[1] (see the signalling hypothesis discussed in the introduction). While the paradigm used in this study does not exclude the possibility for such a strategy to exist, there are reasons to prefer an explanation based on binding and retrieval: First, the binding/retrieval hypothesis is more parsimonious than the strategy account because it assumes only one possibility (binding of features that are retrieved upon repetition) as opposed to two alternatives in the case of the strategy account (If S repeats, repeat R/if S changes, change R). Second, while the lower correlations in change trials fit both explanations, in the case of a strategy, one would expect a much larger difference between repetition and change trials. Specifically, one may expect a negative correlation between the prime and probe in the case of tone changes. Finally, a strategic account would have to be extended to explain results using continuous measures like force and duration that do not use a categorical distinction ('weak' or 'forceful'), like the experiments described in Varga, Pfister, et al. (2022).

In conclusion, the results presented in this study suggest that 1) the repetition/alternation of auditory stimuli by itself is not enough to produce the reaction time effects attributed to binding and retrieval, and 2) continuous (non-categorical) properties of simple actions become bound to and retrieved by auditory stimuli, especially when these properties have a wider range and are task-relevant.

CRediT authorship contribution statement

Sámuel Varga: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. **Roland Pfister:** Conceptualization, Methodology, Writing – review & editing. **Bence Neszmélyi:** Conceptualization, Methodology, Writing – review & editing. **Wilfried Kunde:** Conceptualization, Methodology, Writing – review & editing. **János Horváth:** Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Resources, Software, Supervision, Writing – review & editing.

Declaration of competing interest

The authors have no competing interests to declare.

Data availability

Data and analysis code for Experiments 1 & 2 are available on the Open Science Framework: https://osf.io/wch2e/

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actpsy.2024.104147.

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[1] *Note.* In this study, a change in response would mean an alternation between weak and forceful presses.

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