Action representations in prevention behavior: Evidence from motor execution

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Abstract

Human actions sometimes aim at preventing an event from occurring. How these to-be-prevented events are represented, however, is poorly understood. Recent proposals in the literature point to a possible divide between effect-producing, operant actions, and effect-precluding, prevention actions, suggesting that the control of operant actions relies on codes of environment-related effects whereas prevention actions do not. Here we report two experiments on this issue, showing that spatial features (Experiment 1) as well as temporal features (Experiment 2) of a to-be-prevented event influence actions in the same way as corresponding features of to-be-produced effects. This implies that selecting and executing prevention actions relies on anticipated environmental changes, comparable to operant actions.

Keywords: Prevention, action representation, movement trajectories, response durations

Introduction

Actions are an agent’s interface to the environment. Their impact on the agent’s environment can take one of two forms: Actions can be executed to produce a desired effect (operant actions), or they can be executed to prevent an undesired event from occurring (prevention actions). Operant actions have long been in the spotlight of research on human action control. A line of research that is particularly relevant for the present work aimed at elucidating how intentions – often in the form of categorical goal representations – shape the ensuing body movement when enacting an intention (Marteniuk et al., 1987; Searle, 1980). Whether or not such a direct interplay of intentions and motor performance exists had been questioned by philosophical accounts that posited a conceptual divide between a “prior” intention that does not directly feed into motor performance as compared to an “intention in action” that governs overt movements (Searle, 1980). Empirical findings refuted this position, however, by showing that high level goals such as cooperating vs. competing with another agent indeed shape overt movement trajectories and kinematics (Ansuini et al., 2014; Georgiou et al., 2007; Sartori et al., 2009).

Recent findings thus suggest that intentions related to upcoming changes in the agent’s environment permeate action representations up to the level of precise motor planning. But do these conclusions hold for both types of actions, i.e., operant and prevention actions alike? Several factors cast doubt on this hypothesis and suggest that the impact of goals on motor performance is limited to the operant case. For instance, prevention actions come with particular motivational side-effects that interfere with successful goal pursuit (Higgins, 1998). Speaking even more directly to the issue of action representations, we recently observed that only operant actions give rise to temporal binding, a perceptual illusion affecting the perceived timing of actions and events triggered by these actions, whereas this perceptual illusion was absent for prevention actions (Pfister et al., 2021). Absent temporal binding, in turn, might suggest that prevention actions were not associated with their effects on the environment, at least not on an implicit level of perceptual processing. This would entail that operant and prevention actions would be represented in a fundamentally different way. However, temporal binding requires extended monitoring after action execution, and such monitoring might not occur if the success of a prevention action is sufficiently predictable. If an implicit influence in prevention actions appeared only in earlier stages during action execution, our previous measures would not have been able to detect it. The present research thus set out to test if the two types of actions can still be covered in a parsimonious framework or if they require a fundamentally different theoretical treatment.

To investigate whether to-be-prevented events become included in action representations, thus being able to shape motor control, we addressed situations in which we manipulated the direct consequences of operant and prevention actions alike. Such immediate action-effect chains are an ideal testbed for the present research question because these situations can be described elegantly with the mechanisms proposed by the theoretical framework of ideomotor action control (Greenwald, 1970; Hommel, 2009; Kunde, 2001; Pfister, 2019; for relations of ideomotor theorizing to philosophical work on intentionality, see Stock, 2004). Ideomotor approaches assume that agents acquire bidirectional associations between their body movements and subsequent perceptual changes. Actions therefore become represented in terms of the effects they produce, ascribing action effects an essential role for selecting, planning, and initiating overt body movements (Kunde et al., 2004; Shin & Proctor, 2012; Wirth et al., 2016). Thus, systematically manipulating the relation between body movements and subsequent action effects provides a tool to empirically assess whether the impact of anticipated effects extends beyond categorical action selection to actual action execution. Here, we applied this logic to investigate whether spatial features (Experiment 1) and temporal features (Experiment 2) of to-be-produced/ -prevented events impact the execution of operant and prevention actions differently.

Experiment 1

The design of the first experiment builds on prior work using a mouse-tracking setup to assess the role of anticipated action effects for operant actions (Pfister, Janczyk, et al., 2014; Wirth et al., 2015). Participants of these previous studies performed a speeded classification task requiring them to control an avatar on screen by moving a computer mouse. Reaching a left or right target area with the avatar triggered changes in the visual scene either to the left or the right of the screen. Crucially, these studies manipulated the mapping between the target of the avatar's overt movement and the resulting visual effect. In a compatible mapping, movements to the right caused a visual change on the right side, whereas in an incompatible mapping, movements to the right caused a visual change on the left. Results revealed that the trajectory of the mouse cursor was indeed biased towards the position of the anticipated action effect.

Experiment 1 of the present study employed this tried-and-tested experimental setup to elucidate the representational content of prevention actions. Participants thus controlled the experimental environment not only by evoking perceptual events, but also by preventing the occurrence of such events. To-be-prevented visual events occurred at a predictable location and at a predictable point in time if no action was taken, and performing the appropriate action prevented the change with 100% contingency. Further, we manipulated the relation between the target of the avatar's overt movement and the location of the ensuing action effect, resulting in spatially compatible and incompatible mappings. We examined whether acting to prevent a specific event would shape participants' trajectories in a similar way as a visual event caused by one's action. If the prevented event does not bias trajectories (opposed to what has previously been reported for anticipated produced events in the environment), this would suggest that operant and prevention actions draw upon fundamentally different cognitive foundations. If, however, a reliable trace of the to-be-prevented event emerged in the trajectory of prevention actions, this would promote a view in terms of shared mechanisms instead.

Methods

Open Science Statement

This experiment was pre-registered prior to data collection. Preregistration, all data, and analysis scripts are available at the Open Science Framework (https://osf.io/q3acw/).

Participants

Forty-eight participants (mean age = 27.5 years, standard deviation = 9.3; 41 female, 7 male) took part in this online study, provided informed consent, and received monetary compensation. The sample size was planned relative to the effect-size estimates of previous work on the impact of operant action effects on trajectory measures (e.g., Cohen's $d_z = \frac{t}{\sqrt{N}} = 0.76$ for the effect on area under the curve of Experiment 2 in Pfister, Janczyk, et al., 2014). Our sample size thus promised a high power of $1 - \beta > .99$ for detecting compatibility effects in prevention actions if they were of similar size, even when calculating with a dropout rate of 33%. Five participants were excluded, two due to success rates below 2/3 and three due to not executing the task as instructed with an external computer mouse.

Apparatus and Stimuli

All stimuli were rendered against a white background at a resolution of 1024 px × 768 px. An avatar (21 px × 45 px) was shown at the cursor position and participants had full control over its movement.

The screen was divided by two grey walls (60 px height), located at 137 px and 634 px from the upper edge of the screen to the walls' midline (see Fig. 1). A door (86 px × 83 px) was positioned centrally within the lower wall and served as the starting position. The upper wall had two doors with the midpoints of the doors located 262 px from the left and right edge, respectively. Buttons (50 px × 50 px) located 97 px below the doors served as opening mechanism (indicated by an open lock symbol on the button) or as locking mechanism (indicated by a closed lock symbol). They represented the end point of the trajectories, resulting in a movement trajectory of 250 px × 400 px from the starting position (center to center). Depending on their color, buttons opened or locked either the door on the side of the button (compatible mapping: grey button) or on the other side (incompatible mapping: golden button).

The to-be-produced or to-be-prevented stimuli consisted of two angels (blue vs. yellow) for operant actions and two devils (red vs. green) for prevention actions. Each stimulus had a fixed door for each participant (e.g., blue angel: left; yellow angel: right; green devil: left; red devil: right), and the mapping of stimulus color and door location was counterbalanced across participants. In each trial, one of those stimuli was placed behind one of the upper doors, whereas the other door was left uninhabited. Which stimulus was relevant for the current trial was signaled to participants via text (e.g., “Yellow angel!”; German original: “Gelber Engel”) that was displayed in the middle of the top wall upon trial start. Participants performed the task online and were instructed to use an external computer mouse to control the avatar.

Procedure

The experiment consisted of 6 blocks with 52 trials each. Prior to the experiment, participants were able to familiarize themselves with the design and explore the different stimulus-door mappings and the functionality of the buttons. Action type varied blockwise between operant (O) and prevention (P) blocks (block order counterbalanced across participants: OPOPOP vs. POPOPO), while the spatial compatibility mapping was manipulated trialwise. Prior to each trial, the participants’ avatar spawned at the bottom of the screen, and they had time to prepare for the current compatibility mapping, as the color of the lock symbol was already visible. Participants moved to the lower door at leisure. Reaching this starting position started the trial after a randomly chosen dwell time of 300 or 400 ms (to prevent impulsive movement initiation after a fixed interval). The lower wall vanished, and the imperative text stimulus was displayed in the upper wall, allowing participants to infer the required movement direction. Participants had 3,000 ms to move their avatar towards the corresponding button, thereby opening doors for angels or locking doors for devils. If no button was reached 3,000 ms after the entrance door opened, the trial counted as omission, and either no door opened (operant actions), or the announced door opened, and the respective devil emerged (prevention actions). If the wrong button was reached, an empty door was shown (operant actions), or the announced door opened, and the respective devil emerged (prevention actions). Whenever a devil appeared, an unpleasant buzzer sound was played for 1,000 ms. Colliding with the top wall cancelled the trial immediately and was followed by an error message.

Participants earned 10 points for each correctly opened door with an angel. If a door with a devil was not locked in time or the wrong door was locked, participants lost 10 points. At the end of the experiment, their overall score was converted into a monetary bonus.

Data Treatment

We extracted initiation time (IT), movement time (MT), area under the curve (AUC), and maximum absolute distance (MAD) from the trajectories of each trial. IT was measured as the time from the onset of the imperative stimulus until the cursor left the starting area. MT was measured from this point in time until the cursor hit the end area. AUCs were computed as the signed discrete integral between the executed and the optimal trajectory (straight line from start to end coordinates), and MADs were computed as the maximum signed Euclidean distance between the executed and the optimal trajectory. Deviations towards the opposite target area counted as positive, whereas deviations in the other direction counted as negative. We flipped all movements to the right, time-normalized the coordinates of each trial with linear interpolation before computing AUCs and MADs, and used the resulting normalized trajectories for plotting (Wirth et al., 2020).

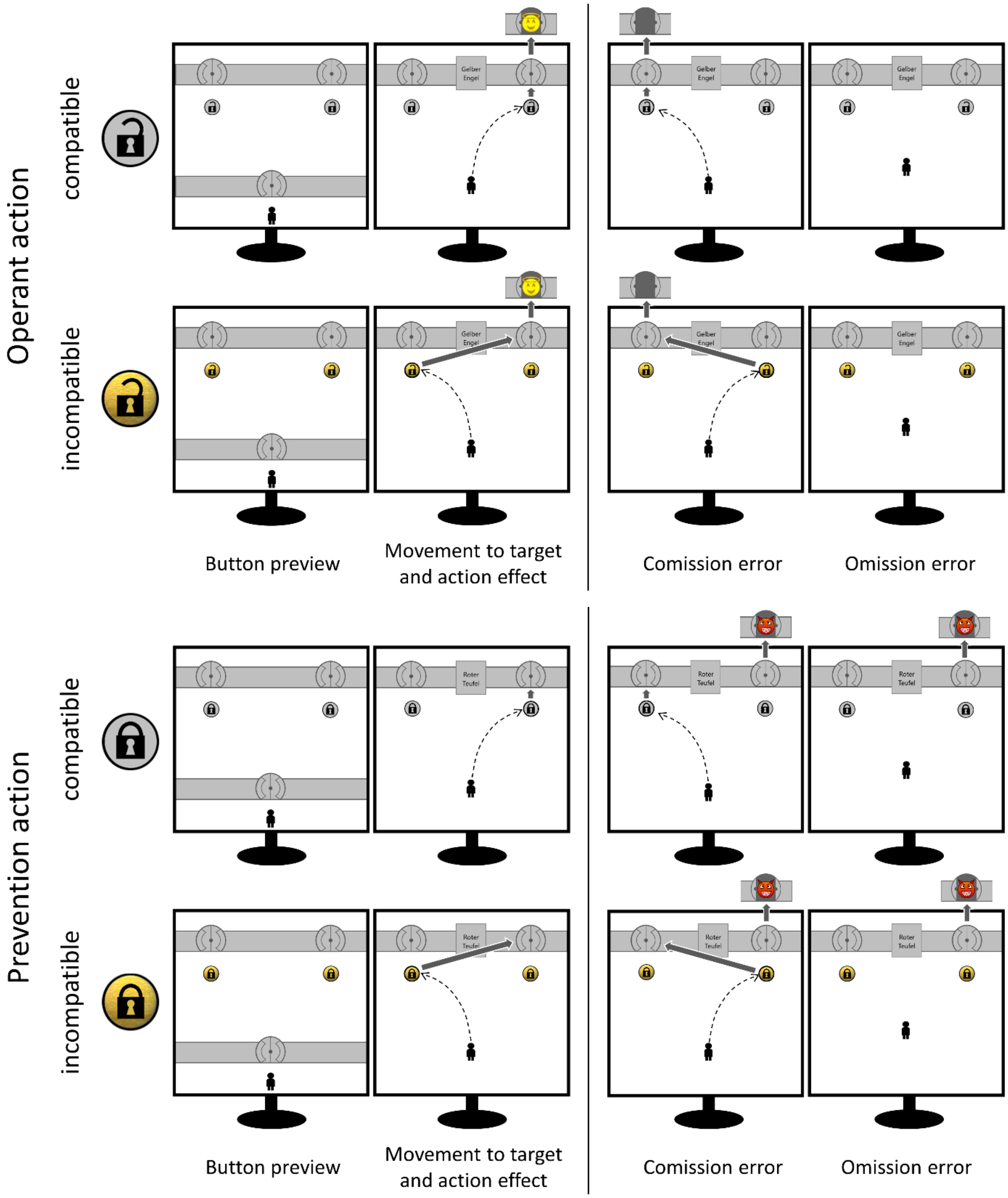

***Figure 1. Trial procedure for operant and prevention blocks in Experiment 1.** Participants saw a preview of the current compatibility mapping, as indicated by the color of the lock button, and started the task at leisure by moving towards the lower door. The actual trial featured an imperative stimulus indicating which door was relevant in the current trial. Participants then had to move the avatar to a button to open or lock the corresponding door. Afterwards the action effect was presented for successful operant actions. Successful prevention actions did not yield any additional changes but prevented a negative event instead.*

Results

Trials with commission errors (6.0%) or omissions (1.1%) were excluded from all analyses. We removed trials as outliers if any of the four variables deviated more than 2.5 standard deviations from the corresponding cell mean, calculated separately for each participant and condition (7.7%). The remaining 85.3% of the overall trials were then averaged and analyzed via 2 × 2 analyses of variance (ANOVAs) with action type (operant

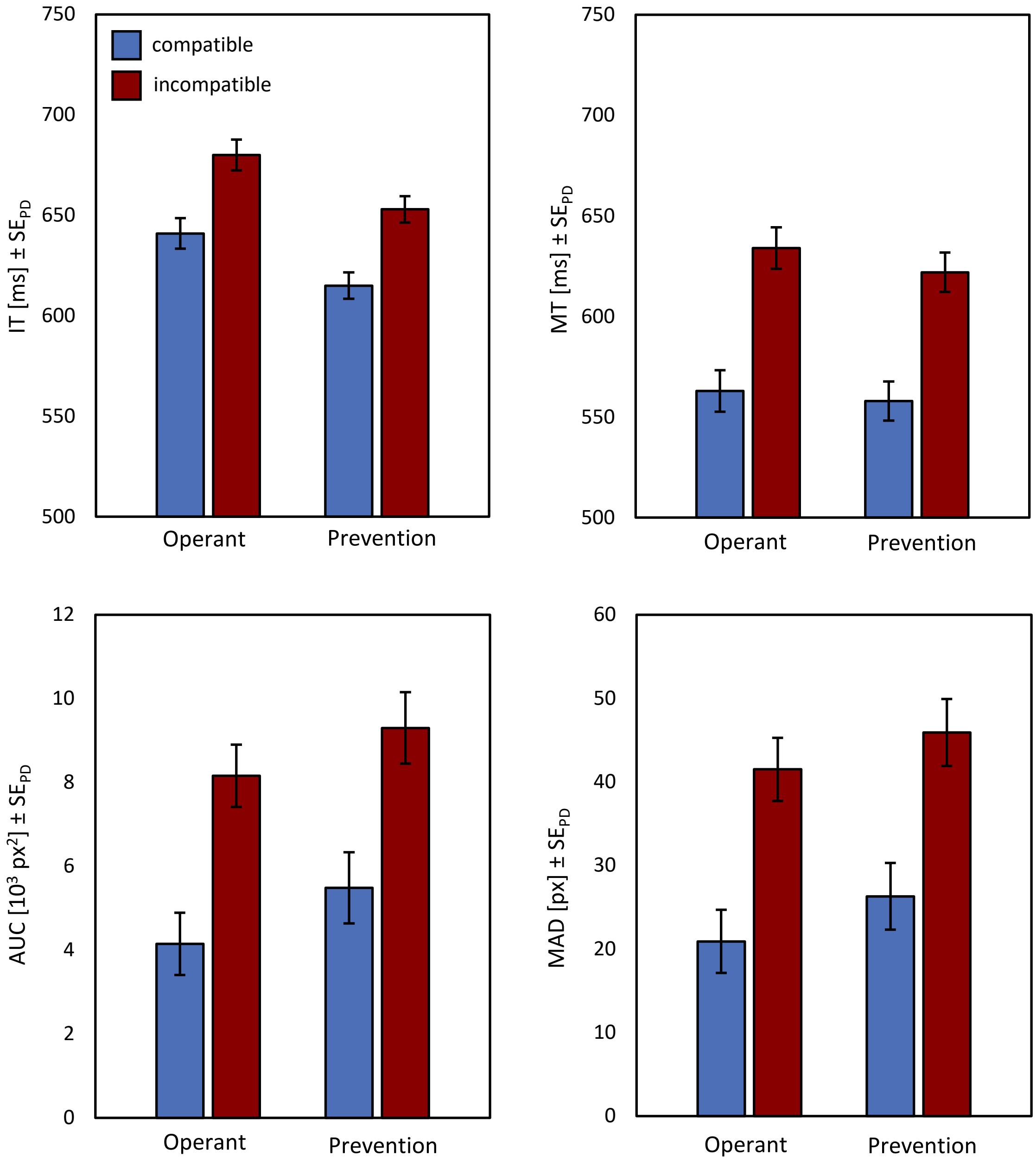

Figure 2. Results of Experiment 1 concerning initiation time (IT), movement time (MT), area under the curve (AUC), and maximum absolute distance (MAD). *Error-bars represent standard errors of paired differences, computed separately for each comparison of compatible and incompatible action-effect mappings (Pfister & Janczyk, 2013).*

vs. prevention) and compatibility mapping (compatible vs. incompatible) as within-subject factors. Figure 2 shows the results of these analyses, Figure 3 visualizes the corresponding trajectories.

Initiation Time

Actions were initiated faster with a compatible mapping than with an incompatible mapping (628 ms vs. 666 ms), $F(1, 42) = 43.64$, $p < .001$, $\eta_p^2 = .51$. Further, prevention actions were initiated faster than operant actions (634 ms vs. 660 ms), $F(1, 42) = 5.59$, $p = .023$, $\eta_p^2 = .12$. The impact of the compatibility mapping did not differ across action types, $F < 1$.

Movement Time

Movements were faster with a compatible than with an incompatible mapping (561 ms vs. 628 ms), $F(1, 42) = 62.06$, $p < .001$, $\eta_p^2 = .60$. There was no significant main effect of action type, $F < 1$, and no interaction, $F < 1$.

Area Under the Curve

Compatible mappings came with consistently smaller AUCs than incompatible mappings (4.82×10^3 px^2 vs. 8.73×10^3 px^2), $F(1, 42) = 33.77$, $p < .001$, $\eta_p^2 = .45$. Prevention

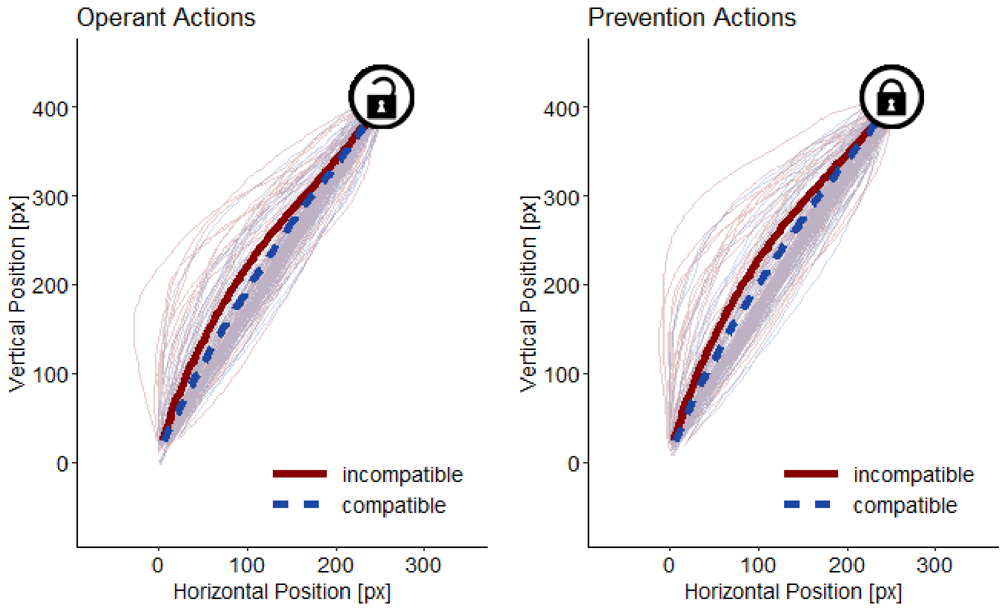

Figure 3. Average time-normalized movement trajectories for Experiment 1. *The bold line marks the averaged trajectory across the entire sample whereas the lighter lines show mean trajectories of individual participants.*

actions came with descriptively larger AUCs than operant actions (7.39×10^3 px^2 vs. 6.15×10^3 px^2), but this main effect was not significant, $F(1, 42) = 3.69$, $p = .061$, $\eta_p^2 = .08$. Again, action type and compatibility mapping did not interact, $F < 1$.

Maximum Absolute Distance

Compatible mappings gave rise to smaller MADs than incompatible mappings (23.6 px vs. 43.7 px), $F(1, 42) = 37.36$, $p < .001$, $\eta_p^2 = .47$. There was neither a significant main effect of action type, $F(1, 42) = 2.60$, $p = .114$, $\eta_p^2 = .06$, nor an interaction, $F < 1$.

Follow-up Analyses

At first glance, the data seem to suggest an influence of the to-be-prevented event on movement trajectories, as we observed a bias of the trajectory towards the anticipated (non-)effect in both the operant and the prevention condition. This would imply that not only operant, but also prevention actions are represented in terms of their anticipated (non-)effects.

More fine-grained analyses of the trajectory data challenge this interpretation, however. Specifically, earlier results suggested that anticipated action effects can influence movement trajectories at different stages during action execution, resulting in a maximum deviation from an ideal, straight trajectory either in the second half of the movement (Exp. 1 in Pfister, Janczyk, et al., 2014) or in the first half already (Exp. 2 in Pfister, Janczyk, et al., 2014). The present data also indicate that a substantial number of trajectories came with marked deviations already very early in the movement, right after action initiation (see Fig. 4A-C). Such early deviations can either indicate direct priming of movements towards the location of to-be-produced or to-be-prevented effects, which would be consistent with the above interpretation of the main results (for evidence of such motor priming, see Knuf et al., 2001; Prinz et al., 2004; Hommel, 2009; Shin et al., 2010; Paulus et al., 2011). However, this pattern may also suggest initial decision errors to approach the wrong target, which were corrected during later stages of the movement.

Knowing whether the observed compatibility effects can be explained in terms of such initial decision errors is critical because it would imply a different theoretical interpretation: If the observed effects arise due to initial decision errors, this pattern would suggest that the influence of the to-be-prevented event is restricted to action selection. A role of anticipated effects for later movement planning and control, by contrast, can only be inferred if initial decision errors are not able to fully explain the findings.

We therefore repeated our analyses but excluded trials that initially started into the wrong direction and then changed direction during the course of the movement. This was operationalized by excluding trials with x-values smaller than the lowest x-value of the

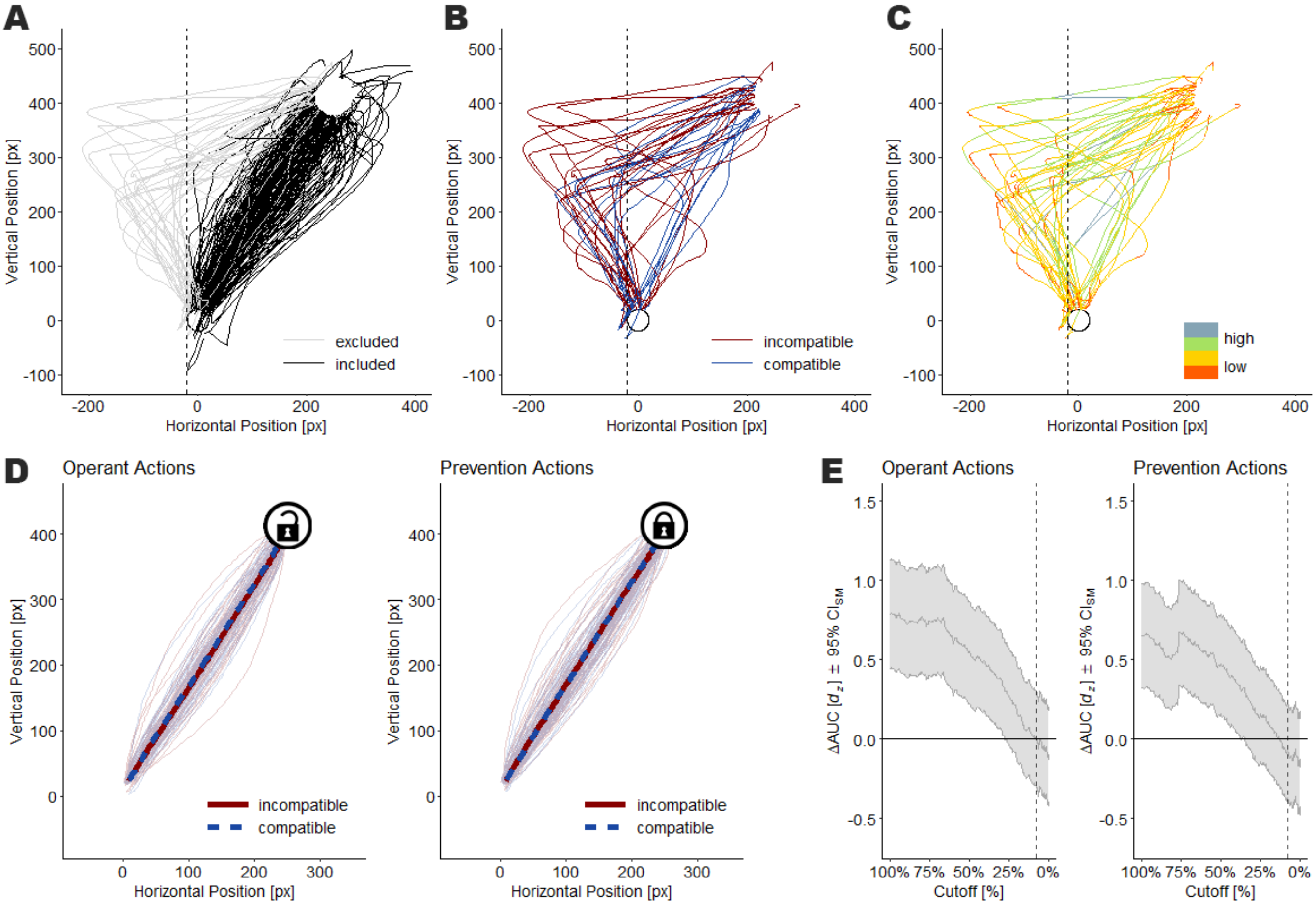

Figure 4. ***Follow-up analyses of initial movement directions in Experiment 1. A.*** *Exemplary single-trial data of one participant, with the trajectory cutoff shown as dashed line. Trials included in the follow-up analysis are shown in black, excluded trials are shown in grey.* ***B.*** *Excluded trials of the example participant. Red lines show incompatible trials, blue lines show compatible trials.* ***C.*** *Excluded trials of the example participant. Color displays the velocity of movement during one trajectory.* ***D.*** *Trajectory data for compatible and incompatible mappings in operant and prevention blocks after excluding trials initially starting into the wrong direction. The bold line marks the averaged trajectory across participants, lighter lines indicate individual participant averages.* ***E.*** *Size of the compatibility effect in AUC for operant and prevention actions, depending on the used cutoff criterion. Abscissas indicate the allowable amount of horizontal movement towards the wrong target, normalized to percentage of the horizontal distance between the center of the start area and the center of the incorrect target area.*

starting area (see Fig. 4A), resulting in a sample of 76.8% of the trials that entered the original analyses (82.8% for compatible operant, 72.7% for incompatible operant, 80.7% for compatible prevention, and 71.0% for incompatible prevention). This exclusion had a sizeable effect on the resulting trajectories (see Fig. 4D). The compatibility effect disappeared for the spatial measures of AUC and MAD, and this conclusion was supported by Bayesian analyses (implemented via the R package BayesFactor, Morey & Rouder, 2018, using a Cauchy scale parameter of $\frac{\sqrt{2}}{2}$; note that we worked with separate Bayesian *t*-tests to overcome limitations of current implementations of Bayesian ANOVAs; Oberauer, 2022; Pfister, 2021). As shown by Figure 4E, a reliable compatibility effect only emerged when relaxing the cutoff to 28.4% of the horizontal distance towards the incorrect target area for the operant condition, and 35.6% for the prevention condition.

Initiation Time

Actions starting in the correct direction were initiated faster with a compatible than with an incompatible mapping (635 ms vs. 685 ms), $F(1, 42) = 66.06$, $p < .001$, $\eta_p^2 = .61$. Further, prevention actions were initiated faster than operant actions (647 ms vs. 673 ms), $F(1, 42) = 4.44$, $p = .041$, $\eta_p^2 = .10$. The impact of the compatibility mapping was similar across action types, $F < 1$, $BF_{01} = 5.76$.

Movement Time

Movements were faster with a compatible than with an incompatible mapping (520 ms vs. 560 ms), $F(1, 42) = 23.07$, $p < .001$, $\eta_p^2 = .35$. All other Fs ≤ 1.42, ps ≥ .241, BF_{01}s ≥ 3.14.

Area Under the Curve

Compatible mappings and incompatible mappings did not differ in terms of their AUC, $F(1, 42) = 0.13$, $p = .721$, $\eta_p^2 < .01$, $BF_{01} = 5.70$. Further, there was no difference between prevention actions and operant actions, $F(1, 42) = 2.80$, $p = .102$, $\eta_p^2 = .06$, $BF_{01} = 1.68$, and no interaction, $F(1, 42) = 0.10$, $p = .748$, $\eta_p^2 < .01$, $BF_{01} = 5.77$.

Maximum Absolute Distance

Compatible mappings and incompatible mappings did not differ in terms of their MAD, $F(1, 42) = 0.06$, $p = .803$, $\eta_p^2 < .01$, $BF_{01} = 5.88$. Further, there was no difference between prevention actions and operant actions, $F(1, 42) = 1.27$, $p = .266$, $\eta_p^2 = .03$, $BF_{01} = 3.36$, and no interaction, $F(1, 42) = 0.72$, $p = .402$, $\eta_p^2 = .02$, $BF_{01} = 4.33$.

Discussion

Experiment 1 showed that trajectories of prevention actions were strongly biased towards the location of the to-be-prevented event. This pattern might indicate that to-be-prevented events are indeed integrated firmly into action representations. Crucially, however, detailed follow-up analyses revealed that the main results were due to a fraction of trials with initial movement towards the to-be-prevented event, which later changed course to the correct target. The same held true for operant actions, and this pattern of results was highly replicable as shown in three follow-up experiments . These follow-up experiments gradually decreased the clear negative connotation of the to-be-prevented event to ensure that the observed result pattern did not derive from an overly attraction of participants' attention due to the high aversiveness of the event, as this could have biased mouse trajectories and instilled initial movements towards the incorrect target. Further, a pure operant experiment precluded the result pattern to stem from a pairing of operant and prevention actions within-participants (for a detailed description of those experiments see Supplementary Experiments 1-3 in the Supplementary Material).

The profound impact of initial movements towards the incorrect target area when aiming to produce or prevent an event at a spatially incompatible location highlights a surprising limitation of previous trajectory analyses for operant actions (e.g., Pfister, Janczyk, et al., 2014; Wirth et al., 2015; Schonard et al., 2021). As it is common in this field, these studies did not include any reports of in-depth analyses of starting directions. The same holds true for most other studies with mouse-tracking methodology (Garcia-Guerrero et al., 2022;

Ye & Damian, 2022; Buttlar & Walther, 2019; Stillman et al., 2017; Dieciuc et al., 2019), and it also applies to current methodological recommendations on trajectory analyses (Hehman et al., 2015; Schoemann et al., 2019; Wirth et al., 2020). Whether and how previous conclusions are affected by such limitations remains to be assessed empirically.

This impact of initial movements in the wrong direction is particularly relevant when trajectory analyses are employed to make precise inferences about the timepoint of an observable influence, as is the case for the present experiments. Here, Experiment 1 as well as all supplementary experiments indicate that there is no detectable influence of effect anticipations on initially correct movements. Whether movements in the wrong direction are best attributed to categorical decision errors or whether they might also be attributed to motor priming by anticipated effects cannot be determined from this data source (note that both contributions are not mutually exclusive). The present experimental setup may thus invite explanations in terms of tapping into high-level propositional representations rather than studying action representations proper (Sun et al., 2022).

To overcome this limitation of the trajectory setup in Experiment 1, we conducted a second experiment on the influence of action effects on action execution, adopting a conceptually related paradigm that enabled us to control for partial errors (Kunde et al., 2004; Thébault et al., 2020).

Experiment 2

Influences of action effects on motor execution were not only reported in continuous mouse tracking paradigms, but also in metric aspects of seemingly discrete keypress designs. In this context, it has been reported that the volume of to-be-produced sounds alters the force of keypresses (e.g., Kunde et al., 2004) and likewise, that temporal features of produced sounds affect temporal properties of actions. For example, when tapping to a beat, adding a delayed sound effect makes participants tap before beat onset (Aschersleben & Prinz, 1995, 1997). Similarly, the duration of keypress responses – i.e., the time between keypress and key release – has been shown to depend on the duration of to-be-produced sounds (Kunde, 2003). Here we capitalized on this latter finding.

Participants of Experiment 2 responded to color stimuli with two different keypresses that predictably produced or prevented tones of different length. The crucial question was whether we would observe an influence of tone length on response durations. Despite its seemingly simple architecture, this experimental setup allows assessing the action execution while at the same time controlling for partial errors. Whereas in Experiment 1 decisional processes and actual action execution could overlap, Experiment 2 nudges participants to complete the decision phase before starting with the action execution, i.e., pressing one specific key. This enables us to clearly disentangle the different processes in this experiment. Observing properties of the produced or prevented event to be mirrored in response durations would thus provide clear-cut evidence for these events to be integrated into corresponding action representations.

Method

Open Science Statement

This experiment was pre-registered prior to data collection. Preregistration, all data, and analysis scripts are available at the Open Science Framework (https://osf.io/q3acw/).

Participants

Forty-eight participants (mean age = 28.5 years, standard deviation = 10.2; 34 female, 14 male) took part in this online study, provided informed consent, and received monetary compensation. This sample size ensures a power of $1 - \beta > .99$ to detect influences on response durations that are similar in size to previous research (Kunde, 2003, Exp. 1, $\eta_p^2 = .58$).

Apparatus and Stimuli

The imperative stimuli were colored rectangles (yellow vs. blue for operant actions; red vs. green for prevention actions) rendered centrally against a black background. The stimulus color prompted a left or right keypress response (“X” vs. “M”). To-be-produced or to-be-prevented effects were sinusoidal tones (short: 50 ms vs. long: 200 ms; 600Hz) that were consistently mapped to a certain response key. Prior to the experiment, the auditory effects were played to the participants, and participants were given the opportunity to adjust the tone volume. The mapping of stimulus colors and tones to response keys was fixed throughout the experiment and counterbalanced across participants.

Procedure

The beginning of a trial was marked by a fixation cross. After 500 ms, the imperative stimulus was presented for 1,500 ms or until two key-events (e.g., keypress and key release) were registered. Pressing and releasing the correct key produced a sound in case of operant actions or prevented a sound for prevention actions. Errors or omissions did not trigger a tone in the operant condition and made the to-be-prevented tone play in the prevention condition. Additionally, appropriate error feedback was displayed for 2,000 ms. The next trial started after an inter-trial interval of 1,000 ms.

The experiment consisted of 8 blocks with 40 trials each. Action type varied blockwise between operant (O) and prevention (P) blocks (block order counterbalanced across participants: PPPPOOOO vs. OOOOPPPP). In contrast to Experiment 1, participants no longer earned or lost points with their responses.

Results

We extracted response times (RTs) and response durations (RDs). RTs were measured as the time from target onset to keypress, RDs as the time from keypress to key release. We excluded trials with commission errors (2.8%) or omissions (0.5%). Trials were considered outliers if RTs or RDs deviated more than 2.5 standard deviations from the corresponding cell mean, calculated separately for each participant and condition (4.4%). The remaining 92.4% of the original trials were then averaged and analyzed via 2 × 2 ANOVAs with action type (operant vs. prevention) and tone length (short vs. long) as within-subject factors (see Fig. 5).

Response Times

No effects were significant, all Fs ≤ 3.22, all ps $\geq .079$, all BF_{01}s ≥ 1.45.

Response Durations

Responses were shorter in duration when followed by a short tone than when followed by a long tone (131 ms vs. 142 ms), $F(1, 47) = 15.36$, $p < .001$, $\eta_p^2 = .25$. Operant actions were descriptively shorter than prevention actions (134 ms vs. 138 ms), but this main effect was not significant, $F(1, 47) = 3.76$, $p = .058$, $\eta_p^2 = .07$, $BF_{01} = 1.14$. Crucially, the effect of the tone length was similar for operant and prevention actions, $F(1, 47) = 0.01$, $p = .915$, $\eta_p^2 < .01$, $BF_{01} = 6.34$.

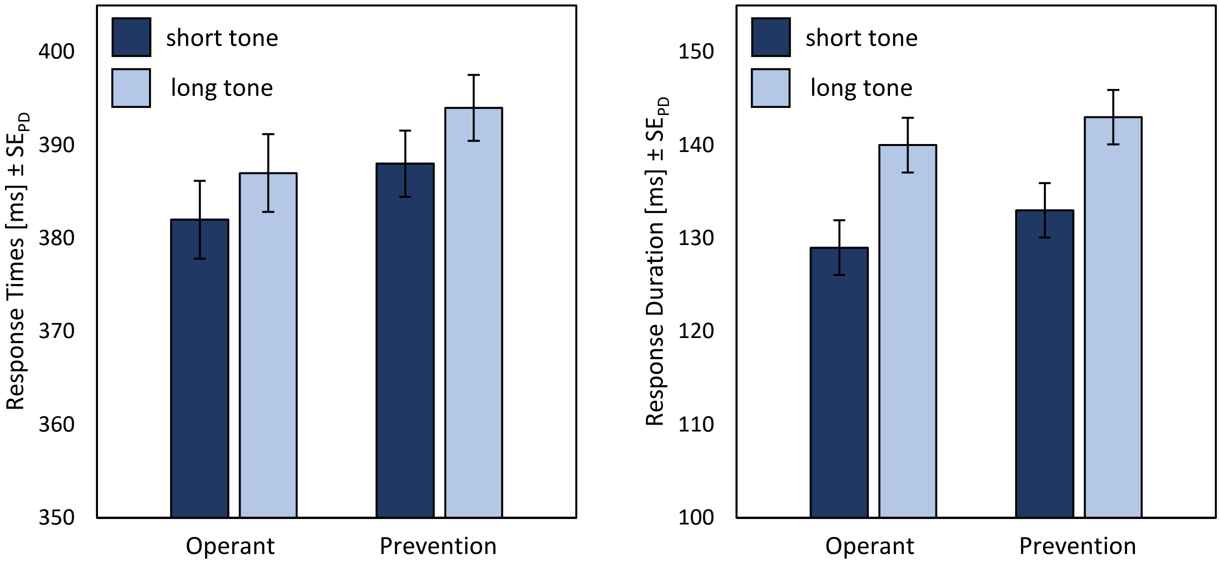

Figure 5. Results of Experiment 2 concerning response times and response durations. *Error-bars represent standard errors of paired differences, computed separately for each comparison of Tone Length (Pfister & Janczyk, 2013).*

Discussion

As expected, we observed an influence of tone lengths on response durations for operant actions. Critically, prevention actions were likewise influenced by the tone length. The results therefore not only corroborate the conclusions drawn from previous experiments for to-be-produced effects, but importantly, they also indicate that the same implicit influence on motor execution exists for to-be-prevented events. This speaks against previous claims that prevention actions are represented solely via propositional mechanisms (Pfister et al., 2021). Yet, we found response durations to be biased towards effect durations (long effects → longer response durations), whereas Kunde (2003) found response durations to be biased away from effect durations (long effects → shorter response durations). However, participants in this latter study were specifically instructed to produce keypresses of a certain duration, whereas response durations were deliberately kept task-irrelevant in the present setup. Previous research indicates that including available information into a representation leads to assimilation, whereas excluding information leads to contrast (Bless & Burger, 2016). In other words, context information perceived as potentially conflicting information evokes contrast (Martin, 1985; Strack et al., 1993) and an action compensates for conflicting aspects of its effects (Aschersleben & Prinz, 1997; Kunde et al., 2004). As response durations were task-irrelevant here, it was not necessary to deliberately counteract the natural bias arising from the length of the ensuing effect. We replicated all findings of this experiment with a direct replication, for details see Supplementary Experiment 4.

General Discussion

The present experiments set out to explore the content of action representations for prevention actions. Fundamental differences between operant and prevention actions had been apparent in previous studies on action-induced perceptual illusions such as temporal binding. Previous work, however, could not assess the representational content during early phases of planning and enacting a prevention action. The present experiments overcame this limitation by studying planning and execution of prevention actions. Results from movement trajectories (Experiment 1) and from response durations (Experiment 2) indeed indicate that to-be-prevented events are represented during such early phases of prevention actions.

That to-be-prevented events affect prevention *decisions* seems obvious – i.e., the truism that certain events can motivate people to perform a prevention action. However, the present data clearly show that the influence of the to-be-prevented event goes beyond such initial decision processes and permeates action *planning and execution*. This challenges previous proposals of fundamental differences between operant and prevention actions (Pfister et al., 2021). Our data thus imply that prevented (non-)effects are incorporated into action representations in prevention behavior akin to operant actions. This finding is especially notable as it suggests that the pure mental image of what would have occurred in the absence of prevention behavior is sufficient to evoke the respective action control mechanisms. Whereas operant actions result in the specific perceptual changes the agent aimed at, successful prevention actions do *not* result in the perceptual change the agent aimed to prevent. And even for operant actions, representing events that cannot be perceived directly has been shown to require deliberate efforts to recollect corresponding experiences (Pfister, Pfeuffer & Kunde, 2014; see also Ansorge, 2002; Vogel et al., 2020). In the present experiment, in contrast, the to-be-prevented event is neither necessary for selecting the correct response alternative, nor it is perceived or even expected to appear after successful action. Still, it shapes action execution, comparable to actually perceivable operant action effects.

Action representations in prevention behavior thus seem to comprise a surprisingly strong associative (rather than propositional) component. A purely propositional action representation would imply that people build up a conscious representation of the relationship between one’s action and the following omission of threatening events, solely reflected in explicit evaluations (De Houwer, 2009; Pfister et al., 2021). While a pure propositional account might be able to explain the trajectory biases observed in Experiment 1, it cannot easily accommodate the influence of the to-be-prevented tone on response durations as observed in Experiment 2. Here, it seems most parsimonious to assume an associative component akin to bi-directional action-effect associations that are commonly thought to underlie operant actions (e.g., Kunde, 2003; Thébault et al., 2020). How this component emerges and evolves in prevention actions, where action-effect linkages are less likely to be reinforced, is certainly a topic for future research.

The observed representation of to-be-prevented events might be facilitated by the difficulty that is associated with negation processing (e.g., Just & Carpenter, 1976; Wason, 1959; Seymour, 1977; Wales & Grieve, 1969). So-called *Spinozan memory accounts* assume that representing negated concepts involves two steps: First, the representation of what should be negated, and second, a tag that signals negation (Gilbert, 1991; Gilbert, Krull, Malone, 1990; Wegner, Coulton, & Wentzlaff, 1985). Retrieving negated concepts from memory thus involves the two successive phases of retrieving the affirmative concept first, and then applying the associated tag. Speculatively, the observed influence of to-be-prevented events, i.e., events that should not be, derives from this initial step of memory retrieval. Retrieving the affirmative concept might also contribute to consolidating prevention actions across longer periods of time by reinforcing the association between an action and the to-be-prevented event.

In this context, the strong representation of a not occurring to-be-prevented event is also interesting from a perspective of negative reinforcement and avoidance learning research. In negative reinforcement the omission of a certain event is perceived as rewarding and therefore can increase corresponding behavior. Research in avoidance learning has mainly focused on affective consequences of such omissions to resolve the paradox that behavior can be reinforced although people perceive no consequence when executing an active avoidance action (e.g., Eder & Dignath, 2014, Rescorla & Lolordo, 1965; Solomon & Corbit, 1974; Eder et al., 2015). These accounts suggest that the expectation of a certain negative event evokes fear, and the successful prevention leads to affective consequences, i.e., the reduction/ termination of a negative affective state or the beginning of a contrary positive affective state, being able to drive reinforcement. Our research now complements this field by suggesting that also without clear affective connotations a hardly perceived event itself is sufficient to build up and maintain a strong representation in prevention context that can drive action control and thereby possibly reinforcement.

If prevention actions do indeed draw on associative representations of the to-be-prevented event, it is plausible that operant and prevention actions might interact if performed in close temporal succession (for evidence for an interplay between different compatibility mappings, see, e.g., Duncan, 1977; Lelonkiewicz et al., 2020). Such interplay could be tested when switching rapidly between operant and prevention actions. Particularly interesting questions in this setting relate to situations in which agents aim to produce an event that they had tried to prevent in an immediately behavioral episode (or vice versa). Whether such situations trigger repetition benefits (e.g., Pashler & Baylis, 1991) or whether they pose a challenge to action selection instead (Dalrymple-Alford & Budayr, 1966; Frings et al., 2015) remains to be explored. The same holds true for the role of preparation for upcoming operant or prevention actions (for general findings on task and response preparation, see Los, 2010; Koch & Allport, 2006; Kunde et al., 2004; Shin & Proctor, 2012; Wirth et al. 2016).

Further, an associative and implicit component in prevention actions may also contribute to the finding that people report explicit agency and attribute (not-)occurring sound effects to their actions when acting to prevent or to produce alike (Pfister et al., 2021). It is still under debate by which exact processes the previously used temporal binding is driven (Antusch et al., 2020; Ruess et al., 2020; Schwarz et al., 2019; Tonn et al., 2021), but if temporal binding indeed only has access to underlying cognitive processes of action control in a very limited time window as suggested above, this would once more call for the necessity of a new implicit measurement depicting agentic influences during a broader range of action stages.

Irrespective of how agency can be measured ideally, the present experiments revealed two further methodological insights for experiments on human action control. First, mouse trajectory effects can be driven by a small fraction of responses containing partial errors. As the strength of this impact seems remarkable, future studies should be supplemented by fine-grained analyses. Second, the experiments highlight response durations as a promising approach to study action representations (see also Foerster et al., 2022; Pfister, Neszmélyi, & Kunde, in press; Varga et al., 2022).

In conclusion, the present experiments show implicit mechanisms in action control of prevention actions. Not only intentions related to upcoming produced changes in an agent's environment, but also intentions targeting the prevention of such changes permeated action representations up to the level of precise motor planning.

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Supplementary Material

Three additional experiments replicated the main findings of Experiment 1 and simultaneously addressed potential caveats of the original experimental design. Supplementary Experiment 1 and 2 gradually decreased the clear negative connotation of the to-be-prevented event in Experiment 1 (i.e., monetary loss and unpleasant sound effect). Although this negative connotation is part and parcel of prevention actions in everyday contexts, the high aversiveness of the event in our experiment might have attracted participants' attention particularly strongly to the to-be-prevented event, thereby biasing mouse trajectories and instilling initial movements towards the incorrect target. In Supplementary Experiment 1, participants no longer earned or lost points and therefore the monetary compensation was unrelated to their performance. The unpleasant sound effect, however, was still played in case of unsuccessful prevention. In Supplementary Experiment 2, this unpleasant sound effect was removed as well, resulting in no additional negative events. Both experiments replicated the significant main effect of compatibility mapping in all measures (IT, MT, AUC, MAD). Crucially, when conducting the same follow-up analyses as in Experiment 1, the compatibility effect again disappeared for the spatial measures of AUC and MAD. These two experiments thus replicated the decisive role of movements initially starting into the wrong direction and ruled out that this data pattern emerged from the negative valence in to-be-prevented events.

Supplementary Experiment 3 removed the prevention condition altogether to assess whether the lack of influence on spatial measures for operant actions can be explained by pairing them with prevention actions within-participants. The significant differences between incompatible and compatible trials in all measures (IT, MT, AUC, MAD) and the disappearance of this compatibility effect for the spatial measures in follow-up analyses were again replicated in this pure operant experiment. This confirms that operant actions are likewise heavily impacted by movements initially starting into the wrong direction.

With Supplementary Experiment 4 we further provide a direct replication of Experiment 2. This replication supports the findings of Experiment 2 and shows the expected influence of tone lengths on response durations for operant and prevention actions.

Supplementary Experiment 1

Open Science Statement

This experiment was pre-registered prior to data collection. Preregistration, all data, and analysis scripts are available at the Open Science Framework (https://osf.io/q3acw/).

Methods

Forty-eight new participants (mean age = 25.3 years, standard deviation = 6.0; 42 female, 6 male) took part in this online study, provided informed consent, and received monetary compensation. Seven participants were excluded, two due to success rates below 2/3 and five due to not executing the task with an external computer mouse. Apparatus, stimuli, and procedure were exactly as in the main experiment, but participants no longer gained or lost points and therefore all received the same monetary compensation.

Results

Data were treated and analyzed as in the main experiment. After excluding trials with commission errors (6.1%), omissions (0.7%), and outliers (8.1%), the final sample for statistical analyses consisted of 85.1% of all trials.

Figure S1 shows means for IT, MT, AUC, and MAD as a function of condition, whereas Figures S2 and S3 show the corresponding trajectories for the full analysis and the follow-up analysis without trials initially starting into the wrong direction.

IT. Actions were initiated faster with a compatible than with an incompatible mapping (599 ms vs. 641 ms), $F(1, 40) = 38.41$, $p < .001$, $\eta_p^2 = .49$. However, there was no significant main effect of action type, $F(1, 40) = 2.92$, $p = .095$, $\eta_p^2 = .07$ and no interaction, $F < 1$.

MT. Movements were faster with a compatible than with an incompatible mapping (458 ms vs. 507 ms), $F(1, 40) = 46.97$, $p < .001$, $\eta_p^2 = .54$. However, there was no significant main effect of action type, $F(1, 40) = 1.09$, $p = .302$, $\eta_p^2 = .03$. Action type and compatibility mapping interacted, $F(1, 40) = 5.19$, $p = .028$, $\eta_p^2 = .11$, with a larger compatibility effect for operant actions, $t(40) = 7.85$, $p < .001$, $d = 1.23$, $\Delta = 58$ ms, than for prevention actions, $t(40) = 4.41$, $p < .001$, $d = 0.69$, $\Delta = 40$ ms.

AUC. Compatible mappings came with smaller AUCs than incompatible mappings (5.28×10^3 px^2 vs. 8.68×10^3 px^2), $F(1, 40) = 19.76$, $p < .001$, $\eta_p^2 = .33$. There was no significant main effect of action type, $F(1, 40) = 3.14$, $p = .084$, $\eta_p^2 = .07$. Action type and compatibility mapping interacted, $F(1, 40) = 7.80$, $p = .008$, $\eta_p^2 = .16$, with a larger

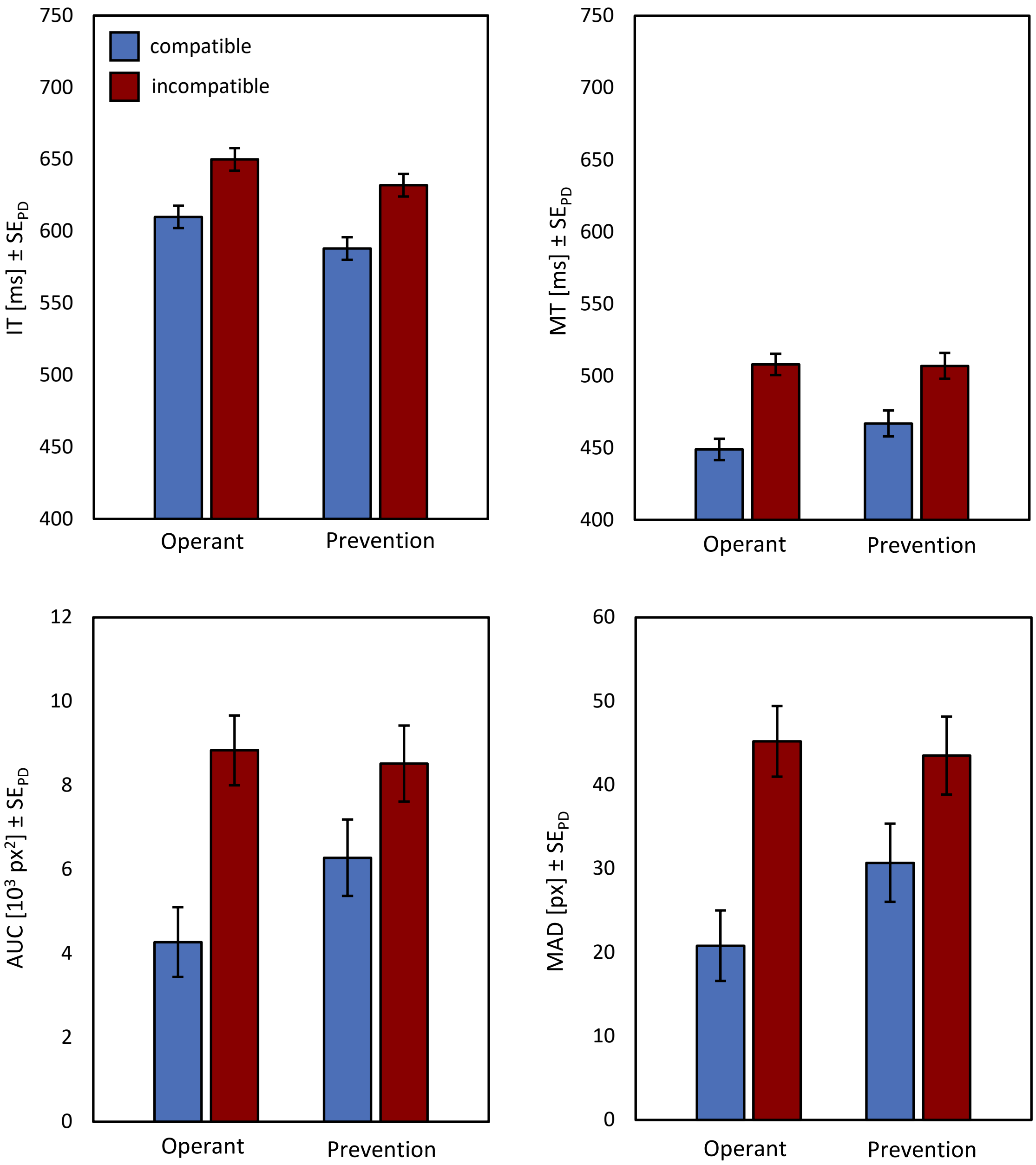

Figure S1. Results of Experiment Supplementary Experiment 1 concerning initiation time (IT), movement time (MT), area under the curve (AUC), and maximum absolute distance (MAD). *Error-bars represent standard errors of paired differences, computed separately for each comparison of compatible and incompatible action-effect mappings (Pfister & Janczyk, 2013).*

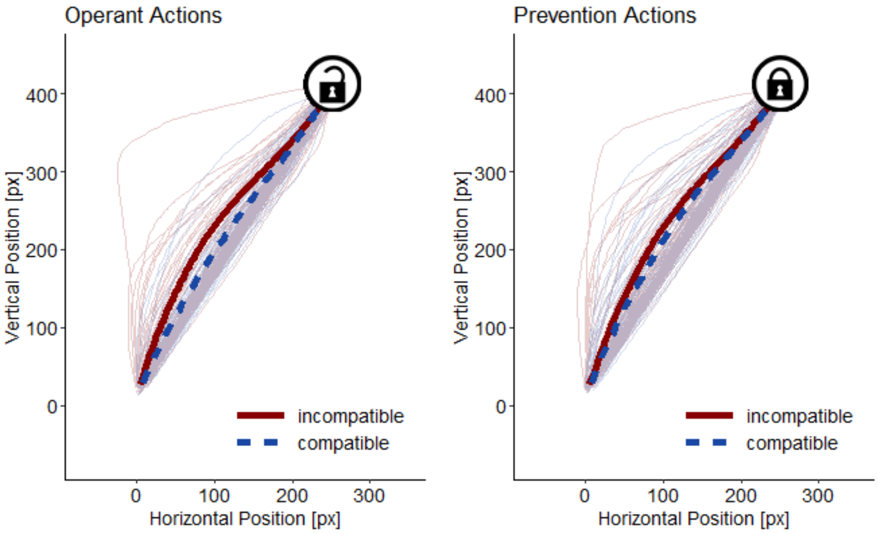

Figure S2. Average time-normalized movement trajectories for Supplementary Experiment 1. *The bold line marks the averaged trajectory across the entire sample whereas the lighter lines show mean trajectories of individual participants.*

compatibility effect for operant actions, $t(40) = 5.48$, $p < .001$, $d = 0.86$, $\Delta = 4.56 \times 10^3$ px^2, than for prevention actions, $t(40) = 2.47$, $p = .018$, $d = 0.39$, $\Delta = 2.24 \times 10^3$ px^2.

MAD. Compatible mappings gave rise to smaller MADs than incompatible mappings (25.8 px vs. 44.3 px), $F(1, 40) = 22.64$, $p < .001$, $\eta_p^2 = .36$. Prevention actions came with descriptively larger MADs than operant actions (37.1 px vs. 33.0 px), but this main effect was not significant, $F(1, 40) = 3.73$, $p = .061$, $\eta_p^2 = .09$. Action type and compatibility mapping interacted, $F(1, 40) = 7.52$, $p = .009$, $\eta_p^2 = .16$, with a larger compatibility effect for operant actions, $t(40) = 5.79$, $p < .001$, $d = 0.90$, $\Delta = 24.4$ px, than for prevention actions, $t(40) = 2.73$, $p = .009$, $d = 0.43$, $\Delta = 12.7$ px.

Follow-up Analysis

For follow-up analyses, trials initially starting into the wrong direction were excluded according to the criterion for the follow-up analyses of the main experiment, resulting in a sample of 77.6% of the trials that entered the original analyses.

IT. Actions were initiated faster with a compatible than with an incompatible mapping (603 ms vs. 655 ms), $F(1, 40) = 47.80$, $p < .001$, $\eta_p^2 = .54$. All other Fs ≤ 2.90, ps $\geq .097$, BF_{01}s ≥ 1.58.

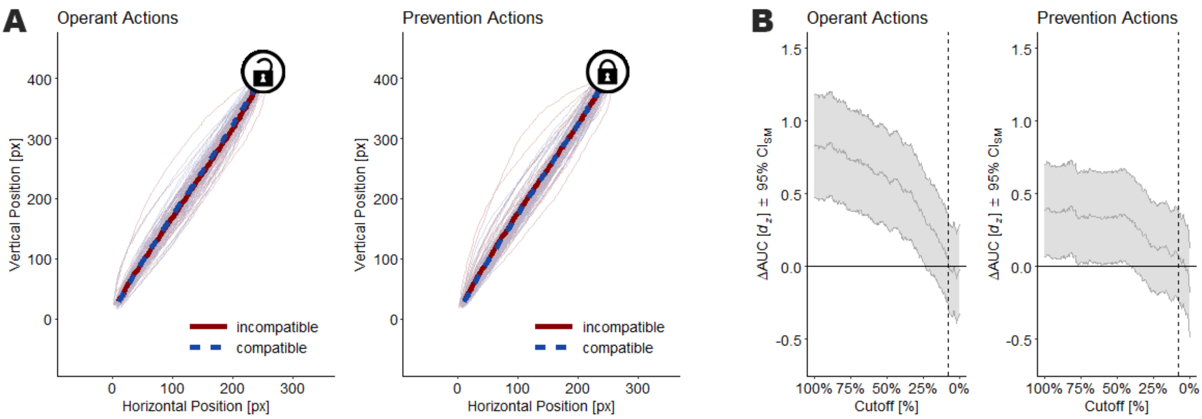

Figure S3. Impact of data exclusion for Supplementary Experiment 1. ***A***. *Trajectory data for compatible and incompatible mappings in operant and prevention blocks after excluding trials initially starting into the wrong direction. The bold line marks the averaged trajectory across participants, lighter lines indicate individual participant averages.* ***B***. *Size of the compatibility effect in AUC for operant and prevention actions, depending on the used cutoff criterion. Abscissas indicate the allowable amount of horizontal movement towards the wrong target, normalized to percentage of the horizontal distance between the center of the start area and the center of the incorrect target area.*

MT. Movements were faster with a compatible than with an incompatible mapping (419 ms vs. 446 ms), $F(1, 40) = 18.84$, $p < .001$, $\eta_p^2 = .32$. All other Fs ≤ 2.35, ps ≥ .133, BF_{01}s ≥ 2.02.

AUC. Compatible mappings and incompatible mappings did not differ in terms of their AUC, $F(1, 40) = 0.04$, $p = .845$, $\eta_p^2 < .01$, $BF_{01} = 5.82$. Prevention actions came with larger AUCs than operant actions (1.46×10^3 px^2 vs. 0.72×10^3 px^2), $F(1, 40) = 6.57$, $p = .014$, $\eta_p^2 = .14$. There was no interaction, $F(1, 42) = 0.21$, $p = .646$, $\eta_p^2 = .01$, $BF_{01} = 5.36$.

MAD. Compatible mappings and incompatible mappings did not differ in terms of their MAD, $F(1, 42) = 0.04$, $p = .842$, $\eta_p^2 < .01$, $BF_{01} = 5.81$. Prevention actions came with larger MADs than operant actions (6.22 px vs. 2.48 px), $F(1, 40) = 10.06$, $p = .003$, $\eta_p^2 = .20$. There was no interaction, $F(1, 42) = 0.82$, $p = .372$, $\eta_p^2 = .02$, $BF_{01} = 4.05$.

Supplementary Experiment 2

Open Science Statement

This experiment was not pre-registered. All data and analysis scripts are available at the Open Science Framework (https://osf.io/q3acw/).

Methods

Forty-eight new participants (mean age = 24.7 years, standard deviation = 5.8; 35 female, 13 male) took part in this online study, provided informed consent, and received monetary compensation. Seven participants were excluded, three due to success rates below 2/3 and four due to not executing the task with an external computer mouse. Apparatus, stimuli, and procedure were exactly as in the main experiment, but participants no longer gained or lost points, and no unpleasant sound effect was played in case of unsuccessful prevention.

Results

Data were treated and analyzed as in the main experiment. After excluding trials with commission errors (8.2%), omissions (0.7%), and outliers (7.4%), the final sample for statistical analyses consisted of 83.6% of all trials.

Figure S4 shows means for IT, MT, AUC, and MAD as a function of condition, whereas Figures S5 and S6 show the corresponding trajectories for the full analysis and the follow-up analysis without trials initially starting into the wrong direction.

IT. Actions were initiated faster with a compatible than with an incompatible mapping (547 vs. 584 ms), $F(1, 40) = 83.85$, $p < .001$, $\eta_p^2 = .68$. Further, prevention actions were initiated faster than operant actions (550 vs. 581 ms), $F(1, 40) = 11.26$, $p = .002$, $\eta_p^2 = .22$. There was no interaction of action type and compatibility mapping, $F < 1$.

MT. Actions were executed faster with a compatible than with an incompatible mapping (496 vs. 544 ms), $F(1, 40) = 75.26$, $p < .001$, $\eta_p^2 = .65$. There neither was a

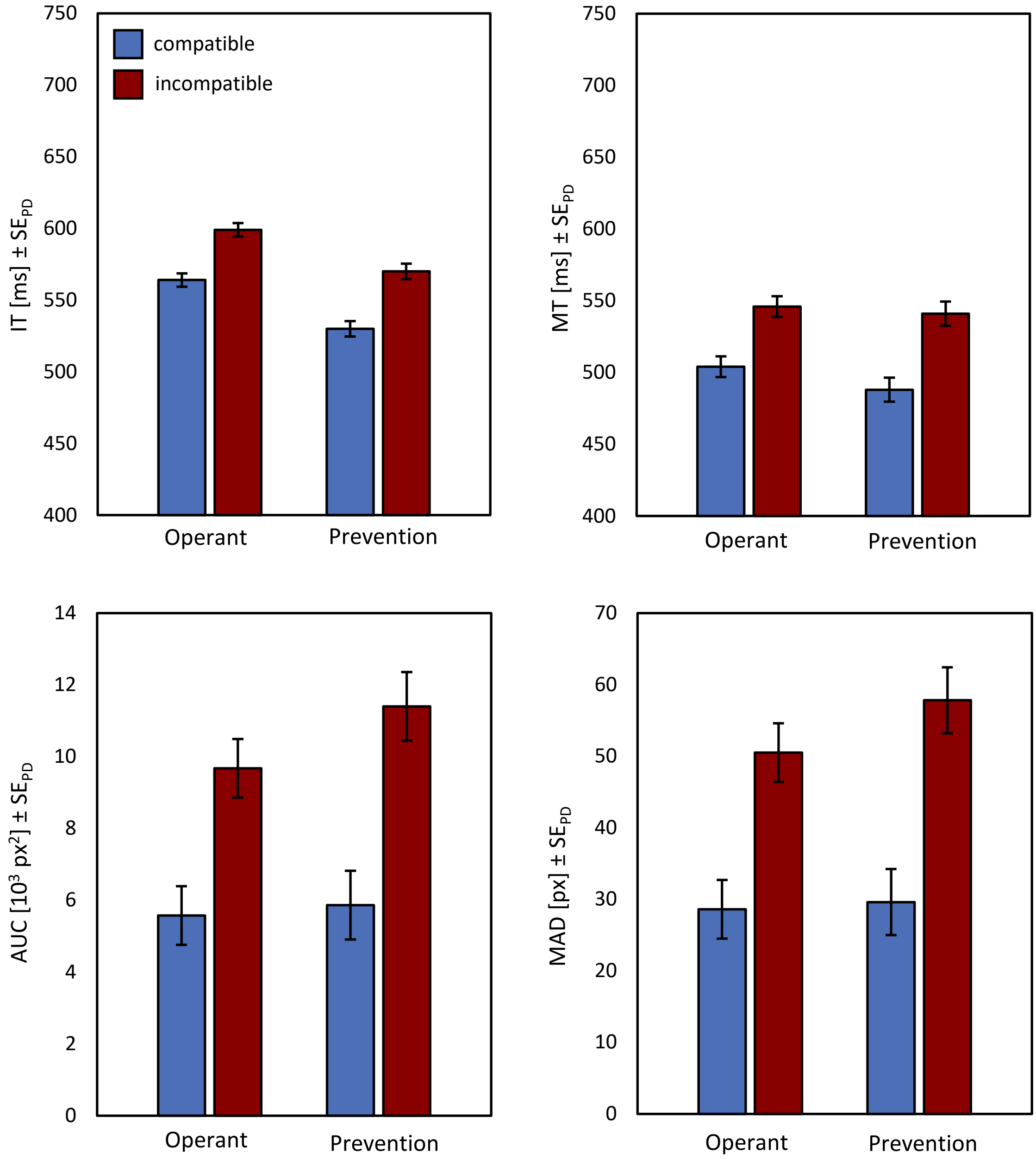

Figure S4. Results of Supplementary Experiment 2 concerning initiation time (IT), movement time (MT), area under the curve (AUC), and maximum absolute distance (MAD). *Error-bars represent standard errors of paired differences, computed separately for each comparison of compatible and incompatible action-effect mappings (Pfister & Janczyk, 2013).*

significant main effect of action type, $F < 1$, nor an interaction, $F(1, 40) = 1.01$, $p = .321$, $\eta_p^2 = .02$.

AUC. Compatible movements came with a consistently smaller AUC than incompatible movements (5.71×10^3 vs. 10.54×10^3 px^2), $F(1, 40) = 43.83$, $p < .001$, $\eta_p^2 = .52$. Prevention actions came with descriptively larger AUCs than operant actions (8.63×10^3 vs. 7.63×10^3 px^2), but this main effect was not significant, $F(1, 40) = 3.77$, $p = .059$, $\eta_p^2 = .09$. There was no significant interaction, $F(1, 40) = 1.95$, $p = .170$, $\eta_p^2 = .05$.

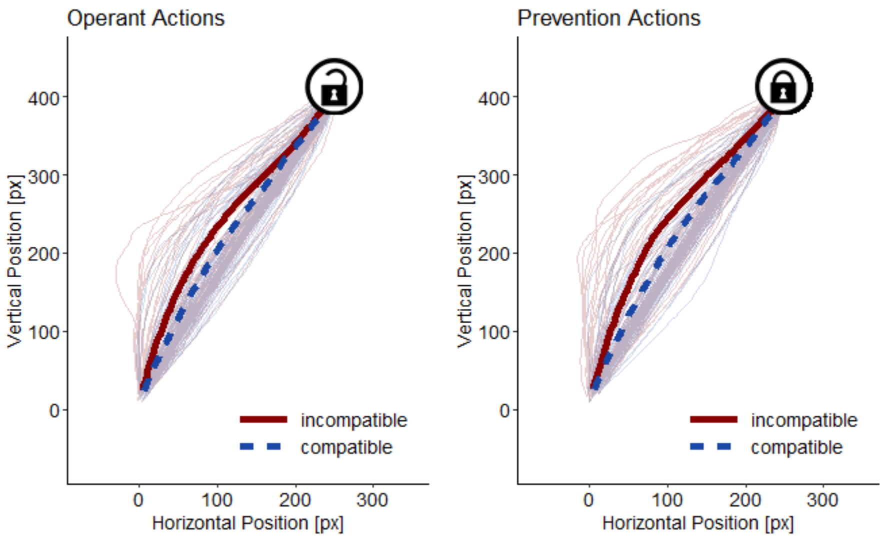

Figure S5. Average time-normalized movement trajectories for Supplementary Experiment 2. *The bold line marks the averaged trajectory across the entire sample whereas the lighter lines show mean trajectories of individual participants.*

MAD. Compatible movements also revealed a smaller MAD than incompatible movements (29.1 vs. 54.2 px), $F(1, 40) = 49.06$, $p < .001$, $\eta_p^2 = .55$. There was neither a significant main effect of action type, $F(1, 40) = 2.77$, $p = .104$, $\eta_p^2 = .06$, nor an interaction of action type and compatibility mapping, $F(1, 40) = 1.64$, $p = .207$, $\eta_p^2 = .04$.

Follow-up Analysis

For follow-up analyses, trials initially starting into the wrong direction were excluded according to the criterion for the follow-up analyses of the main experiment, resulting in a sample of 73.2% of the trials that entered the original analyses.

IT. Actions were initiated faster with a compatible than with an incompatible mapping (554 ms vs. 598 ms), $F(1, 40) = 78.01$, $p < .001$, $\eta_p^2 = .66$. Further, prevention actions were initiated faster than operant actions (559 ms vs. 593 ms), $F(1, 40) = 10.11$, $p = .003$, $\eta_p^2 = .20$. The impact of compatibility mapping was similar across action types, $F(1, 40) = 3.72$, $p = .061$, $\eta_p^2 = .09$, $BF_{01} = 1.10$.

MT. Movements were faster with a compatible than with an incompatible mapping (447 ms vs. 474 ms), $F(1, 40) = 18.54$, $p < .001$, $\eta_p^2 = .32$. All other *F*s < 1, BF_{01}s ≥ 4.02.

AUC. Compatible mappings and incompatible mappings did not differ in terms of their AUC, $F(1, 40) = 0.41$, $p = .527$, $\eta_p^2 = .01$, $BF_{01} = 4.90$. Also, action type had no significant influence, $F(1, 40) = 1.20$, $p = .279$, $\eta_p^2 = .03$, $BF_{01} = 3.39$. Action type and compatibility mapping interacted, $F(1, 40) = 4.95$, $p = .032$, $\eta_p^2 = .11$, with a descriptive, but non-significant compatibility effect for operant actions, $t(40) = 1.76$, $p = .086$, $d = 0.28$, $\Delta = 0.7 \times 10^3$ px^2, and no compatibility effect for prevention actions, $t(40) = -1.11$, $p = .272$, $d = -0.17$, $\Delta = -0.3 \times 10^3$ px^2.

MAD. Compatible mappings and incompatible mappings did not differ in terms of their MAD, $F(1, 40) = 0.75$, $p = .391$, $\eta_p^2 = .02$, $BF_{01} = 4.17$. Action type had no significant influence, $F(1, 40) = 1.43$, $p = .238$, $\eta_p^2 = .03$, $BF_{01} = 3.05$. Action type and compatibility mapping interacted, $F(1, 40) = 4.56$, $p = .039$, $\eta_p^2 = .10$, with a descriptive, but non-significant compatibility effect for operant actions, $t(40) = 1.92$, $p = .062$, $d = 0.30$, $\Delta = 2.9$ px, and no compatibility effect for prevention actions, $t(40) = -0.86$, $p = .397$, $d = -0.13$, $\Delta = -1.1$ px.

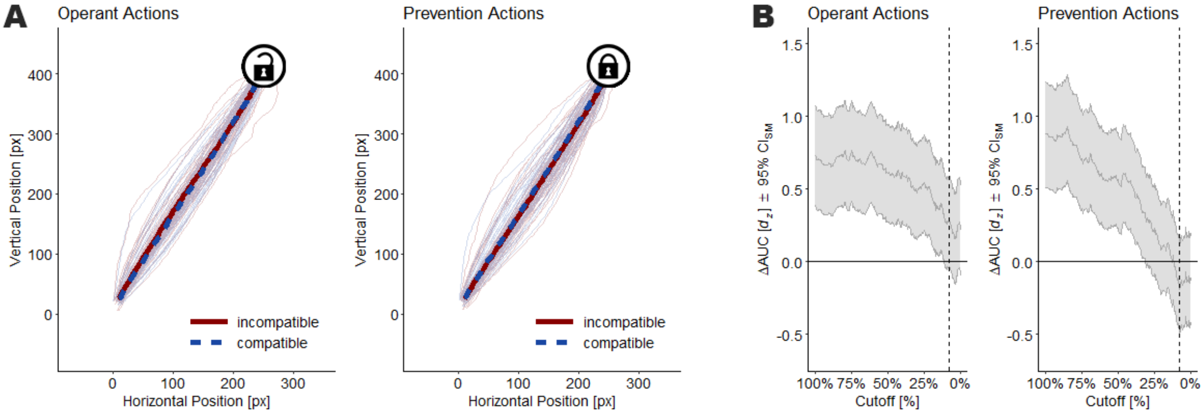

Figure S6. Impact of data exclusion for Supplementary Experiment 2. A. Trajectory data for compatible and incompatible mappings in operant and prevention blocks after excluding trials initially starting into the wrong direction. The bold line marks the averaged trajectory across participants, lighter lines indicate individual participant averages. B. Size of the compatibility effect in AUC for operant and prevention actions, depending on the used cutoff criterion. Abscissas indicate the allowable amount of movement of the horizontal movement towards the wrong target, normalized to percentage of horizontal distance between the center of the start area and the center of the incorrect target area.

Supplementary Experiment 3

Open Science Statement

This experiment was pre-registered prior to data collection. Preregistration, all data, and analysis scripts are available at the Open Science Framework (https://osf.io/q3acw/).

Methods

Forty-eight new participants (mean age = 24.8 years, standard deviation = 7.1; 32 female, 16 male) took part in this online study, provided informed consent, and received monetary compensation. Two participants were excluded due to not executing the task with an external computer mouse. Apparatus, stimuli, and procedure were exactly as in Supplementary Experiment 2, but participants only worked through the operant blocks.

Results

Data were treated as in the main experiment and the compatibility effect was analyzed via paired *t*-tests. After excluding trials with commission errors (4.0%), omissions (1.1%), and outliers (7.6%), the final sample for statistical analyses consisted of 87.3% of all trials.

Figure S7 shows means for IT, MT, AUC, and MAD as a function of condition, whereas Figures S8 and S9 show the corresponding trajectories for the full analysis and the follow-up analysis without trials initially starting into the wrong direction.

IT. Actions were initiated faster with a compatible than with an incompatible mapping (570 vs. 603 ms), $t(45) = 5.04$, $p < .001$, $d = 0.74$.

MT. Actions were executed faster with a compatible than with an incompatible mapping (567 vs. 625 ms), $t(45) = 7.87$, $p < .001$, $d = 1.16$.

AUC. Compatible movements came with a consistently smaller AUC than incompatible movements (7.22×10^3 vs. 11.23×10^3 px^2), $t(45) = 4.56$, $p < .001$, $d = 0.67$.

MAD. Compatible movements also revealed a smaller MAD than incompatible movements (33.6 vs. 54.4 px), $t(45) = 5.03$, $p < .001$, $d = 0.74$.

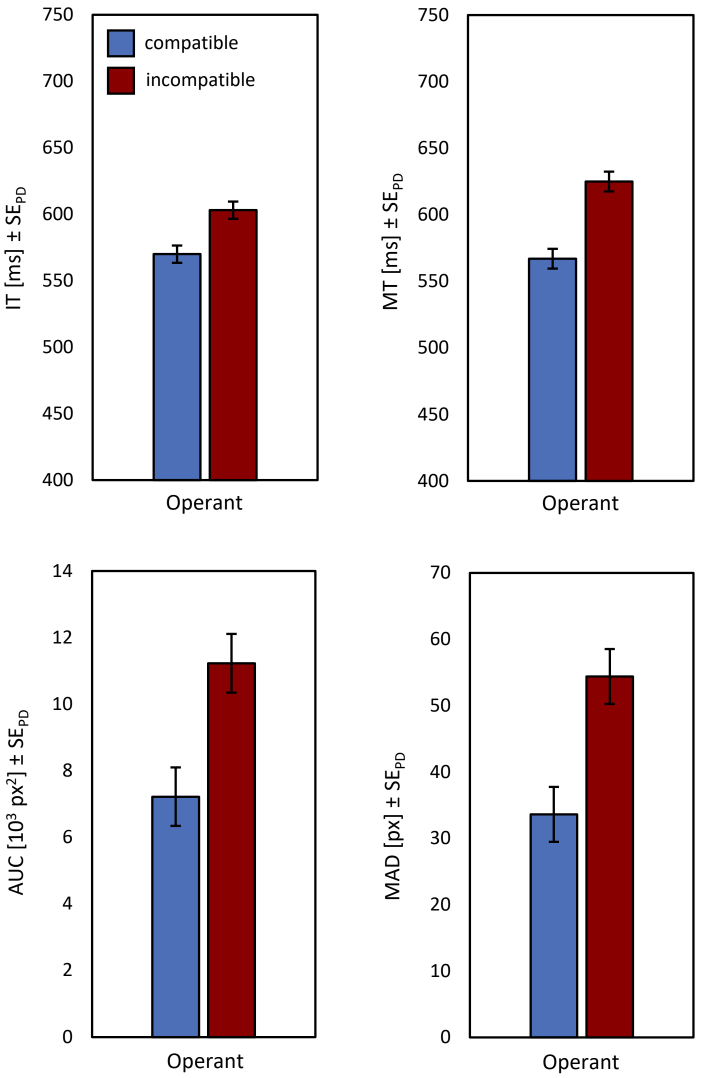

Figure S7. Results of Supplementary Experiment 3 concerning initiation time (IT), movement time (MT), area under the curve (AUC), and maximum absolute distance (MAD). *Error-bars represent standard errors of paired differences, computed separately for each comparison of compatible and incompatible action-effect mappings (Pfister & Janczyk, 2013).*

Follow-up Analysis

For follow-up analyses, trials initially starting into the wrong direction were excluded according to the criterion for the follow-up analyses of the main experiment, resulting in a sample of 73.5% of the trials that entered the original analyses.

IT. Actions were initiated faster with a compatible than with an incompatible mapping (581 vs. 620 ms), *t*(45) = 4.62, *p* < .001, *d* = 0.68.

MT. Actions were executed faster with a compatible than with an incompatible mapping (517 vs. 557 ms), *t*(45) = 4.96, *p* < .001, *d* = 0.73.

AUC. Compatible mappings and incompatible mappings did not differ in terms of their AUC, $t(45) = 1.47$, $p = .149$, $d = 0.22$, $BF_{01} = 2.30$.

MAD. Compatible mappings and incompatible mappings did not differ in terms of their MAD, $t(45) = 1.58$, $p = .120$, $d = 0.23$, $BF_{01} = 1.96$.

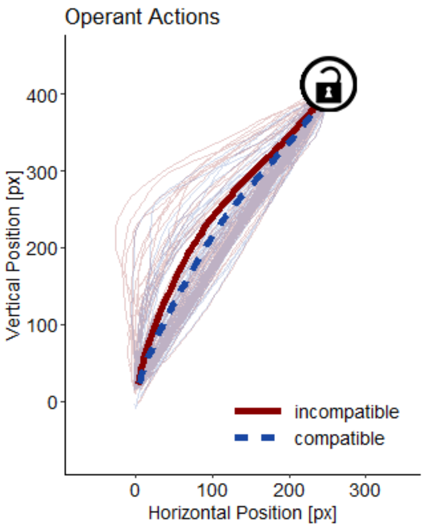

Figure S8. Average time-normalized movement trajectories for Supplementary Experiment 3. *The bold line marks the averaged trajectory across the entire sample whereas the lighter lines show mean trajectories of individual participants.*

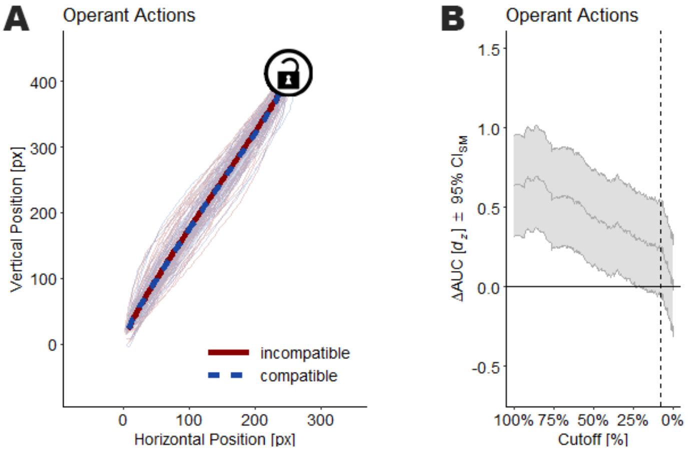

Figure S9. Impact of data exclusion for Supplementary Experiment 3. A. *Trajectory data for compatible and incompatible mappings after excluding trials initially starting into the wrong direction. The bold line marks the averaged trajectory across participants, lighter lines indicate individual participant averages.* ***B.*** *Size of the compatibility effect in AUC for operant actions, depending on the used cutoff criterion. Abscissas indicate the allowable amount of horizontal movement towards the wrong target, normalized to percentage of the horizontal distance between the center of the start area and the center of the incorrect target area.*

Supplementary Experiment 4

Open Science Statement

This experiment was pre-registered prior to data collection. Preregistration, all data, and analysis scripts are available at the Open Science Framework (https://osf.io/q3acw/).

Methods

This experiment is a direct replication of Experiment 2. Number of participants, apparatus, stimuli and procedure as well as data preparation and analysis therefore were the same as in Experiment 2. Forty-eight new participants (mean age = 23.19 years, standard deviation = 4.73; 40 female, 8 male) took part in this online study, provided informed consent, and received monetary compensation.

Results

RTs. RTs were shorter for operant than for prevention actions (379 ms vs. 392 ms), $F(1, 47) = 11.71$, $p < .001$, $\eta_p^2 = .20$**.** All other Fs ≤ 1.77, all ps ≥ .189, all BF01s ≥ 2.79.

RDs. Responses were shorter in duration when followed by a short tone than when followed by a long tone (125 ms vs. 135 ms), F(1, 47) = 16.12, p < .001, ηp2 = .26. All other Fs < 1, BF$_{01}$s ≥ 5.50.

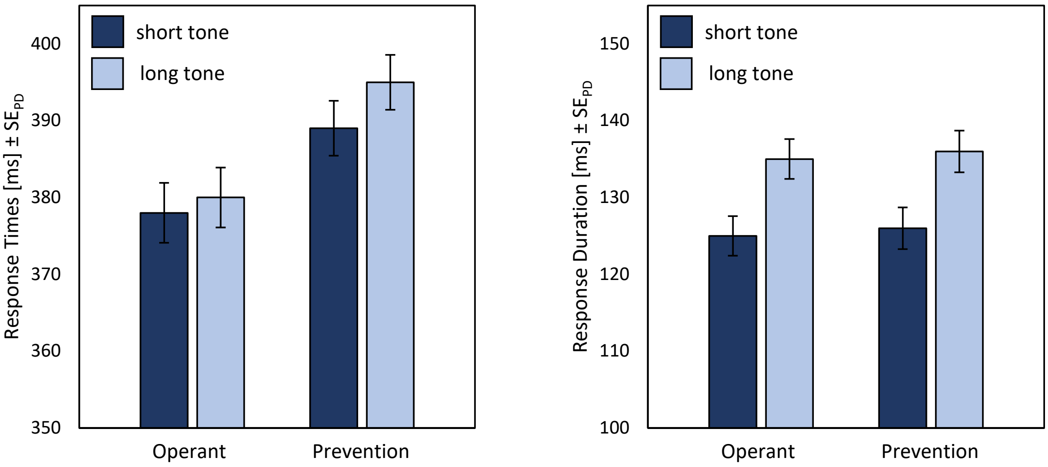

Figure S10. Results of Supplementary Experiment 4 concerning response times and response durations. *Error-bars represent standard errors of paired differences, computed separately for each comparison of Tone Length (Pfister & Janczyk, 2013).*