Motor planning is obligatorily biased by task-irrelevant objects

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Abstract

Goal-directed actions can be biased by the simple presence of non-target stimuli. These interference effects are often attributed to the management of competing motor responses during goal selection. Another possibility is that the mind automatically incorporates salient yet task-irrelevant information into motor planning. Using imitated movements as a test-bed, we explore the effects of non-targets on actions in the absence of both goal selection and response competition. Across five experiments (N=500 adults, preregistered), participants viewed another agent's hand following a unique trajectory to a target, and then moved their own hand to replicate the observed trajectories. Surprisingly, imitated trajectories were consistently repelled by task-irrelevant objects. These effects persisted even when goal uncertainty was eliminated, and emerged at the earliest stages of imitated movements. These results point to an obligatory, bottom-up effect of non-targets on motor planning, where task-irrelevant stimuli automatically shape movements regardless of their relevance to goals.

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Introduction

Perception, attention, and action are tightly intertwined. Even performing the simplest everyday actions – like reaching for a water bottle on your desk – requires parsing a complex, cluttered scene as you plan and execute your movement. Other objects, such as your empty mug of coffee, are not the target of actions but can impede movement or distract attention (See Figure 1A). The role of "non-targets" in visual attention and eye movements has been well documented (e.g., Connor et al., 2004; Doyle and Walker, 2001; Gaspelin and Luck, 2018; Geng, 2014; Van der Stigchel et al., 2006).

A large body of research on attention and action has shown that distracting stimuli can also bias goal-directed actions, including upper-limb reaching movements. Non-target stimuli in the task environment affect both response times during movement planning (Tipper et al., 1992, 2002), and the path the hand or eyes take toward goals (Arai & Keller, 2005; McSorley et al., 2006; Song & McPeek, 2009; Van der Stigchel et al., 2006). These effects are complex: In some cases, distractors function as "attractors" in the environment, drawing movements towards them (Chang & Abrams, 2004; Diedrichsen et al., 2004; Kerzel & Schönhammer, 2013; Moher et al., 2015; Welsh, 2011; Welsh & Elliott, 2005; Welsh et al., 1999). In other contexts, movement trajectories are repelled away from non-targets (Chapman & Goodale, 2008; Howard & Tipper, 1997; Tresilian, 1998; Werner & Diedrichsen, 2002). Accounts of these opposing effects point to multiple factors, including visual salience (Welsh & Elliott, 2005), the spatial layout of the task (Tipper et al., 1997), and the timing of object appearance (Welsh et al., 1999) (See Figure 1B for an example).

Nevertheless, questions remain concerning the nature of interference effects on action. First, why do visual non-targets bias movement trajectories in the first place? A popular theoretical account emphasizes a competition between planned movements towards targets versus non-targets. According to this idea, the mind forms motor plans to targets and non-targets in parallel, such that a motor plan directed at the non-target initially competes with the plan towards the target, driving the movement trajectory *towards* the non-target; given enough time, the distractor-directed plan is then inhibited, repelling the movement trajectory *away* from the non-target (Tipper et al., 1997; Welsh & Elliott, 2004). Neural evidence for such a model suggests that areas like the premotor cortex may simultaneously encode multiple potential reach plans before a target is finally selected (Cisek & Kalaska, 2002, 2005). However, the existence of simultaneous planning of multiple competing movements in the sensorimotor system has been recently challenged (Alhussein & Smith, 2021; Dekleva et al., 2018; Wong & Haith, 2017). Either way, some kind

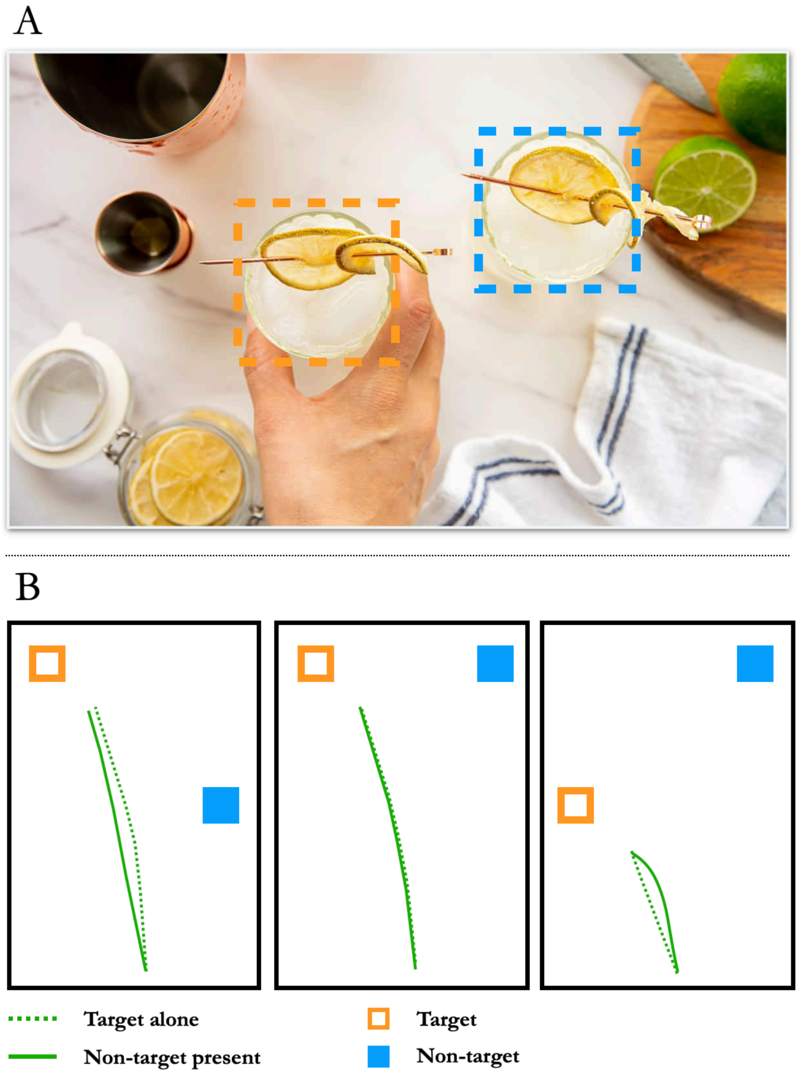

Figure 1: **(A)** Everyday, we move our hands to interact with the various objects in a complex environment. Often, the goal of our action (marked by the orange box) appears with visual distractors (marked by the blue box) in the same scene. While our attention and eyes might be captured by non-target objects, it can be unclear to what extent and in what way our hand movements are affected by those stimuli. **(B)** A schematic illustration of how a distractor interferes with the reaching trajectories to a target, recreated from previous results Tipper et al. (1997). This work reported opposite interference effects caused by a non-target — depending on where a non-target appears, the movement could be veered towards (left) or away from it (right), or not be affected (middle).

of inhibitory function of non-targets – whether during initial formation of a single motor plan or in competition between multiple already-formed plans – is a likely mechanism driving repulsion effects.

What are the necessary and sufficient conditions for non-targets to interfere with reaching movements? According to most models of distracting effects, non-targets bias movements at the level of goal selection (Tipper et al., 1994, 2002). That is, distractors activate an inhibitory process that concerns selecting the end goal of a movement (e.g., grasping a specific object) and suppressing competition from non-targets (e.g., other objects in view). Alternatively, it may be that non-targets affect movements even when goal selection is irrelevant to the task. Here we tested this hypothesis, using a novel approach that alters the fundamental goal of simple reaching movements: imitation.

When imitating another person's movements (e.g., a new dance move), the primary goal is not simply a final end position, but the faithful mimicry of a spatiotemporal trajectory (Bekkering et al., 2000; Heyes, 2001). This makes imitation a surprisingly fitting context to study the nature of non-target interference effects: We here ask if non-targets still bias the kinematics of movement trajectories when the goal of those movements is trajectory imitation and not endpoint selection. If such biases disappear in the imitation setting, it would be consistent with the idea that visual distractors interfere with goal selection only. If non-targets still bias imitated movements, it would suggest a much more fundamental, obligatory link between the visual processing of objects in a scene and motor planning. Our hypothesis was the latter – that non-target biasing effects are baked-in to virtually all volitional movements, even when the goal of a movement is not to select or efficiently reach toward a target, but simply to imitate an observed movement trajectory.

Using hand movement trajectory imitation as a test-bed, over five experiments we found reliable and persistent non-target repulsion effects. Non-targets biased imitated movement trajectories even when there was no uncertainty about the movement end-goal, and over a range of observation and imitation visual contexts. Moreover, non-target biases emerged in the earliest stages of imitated movements, pointing to an automatic, task-irrelevant influence of non-targets on motor trajectory planning. These results may reflect a relationship between bottom-up perceptual processes and action that is more robust than previously believed – visual non-targets produce an automatic influence on movement planning that does not require uncertainty about goals nor decisions.

Open Science Practice

This research received approval from Yale University's local ethics board. For all experiments, we pre-registered the sample size, experimental design, and the main and secondary analyses. A demo of the imitation task can be viewed at https://gen-move.netlify.app/, so readers can experience the experiment as participants did. The data, experiment code, stimuli, and experiment pre-registrations for all studies are available at:

https://osf.io/9s7m6/?view_only=eba1ccecf58941319920449ff6d6c578.

Experiment 1: Non-imitated movements

Our main studies (Experiments 2-5) involved people viewing and then imitating curved movement trajectories, with and without irrelevant objects present. In Experiment 1, we first wanted to establish that *non-imitated* movements – ones with similar trajectory curvature as the imitated movements in later experiments – were subject to classic non-target biasing effects. Thus, our first study aimed to simply replicate previous findings showing repulsion effects in hand movements (Howard & Tipper, 1997; Tipper et al., 1997; Welsh & Elliott, 2004), but with one key manipulation: people were forced to curve their movements around salient visual obstacles, allowing us to generate similar curvature as our later main experiments.

Method

Participants

As stated in our pre-registration, we recruited 100 participants for this experiment from the online platform Prolific (https://www.prolific.co/). A smaller pilot suggested that this sample would have power above 99% to reveal distractor bias effects. This experiment and all others reported here were approved by the [redacted] Institutional Review Board.

Design and procedure

In this task, participants were asked to simply move their mouse to a target while avoiding a large barrier. The target appeared either at the top left or top right region of the workspace, and either alone or with a non-target placed on the opposite side. Each of the four unique trial types was presented 50 times, resulting in 200 trials in total. The order of trial types was randomized.

Figure 2A illustrates the trial types. In half of the trials, participants saw the target (a green box, either on the left or right), a barrier (a black region on the same side as the target), and a start position at the bottom of the workspace (Target Only

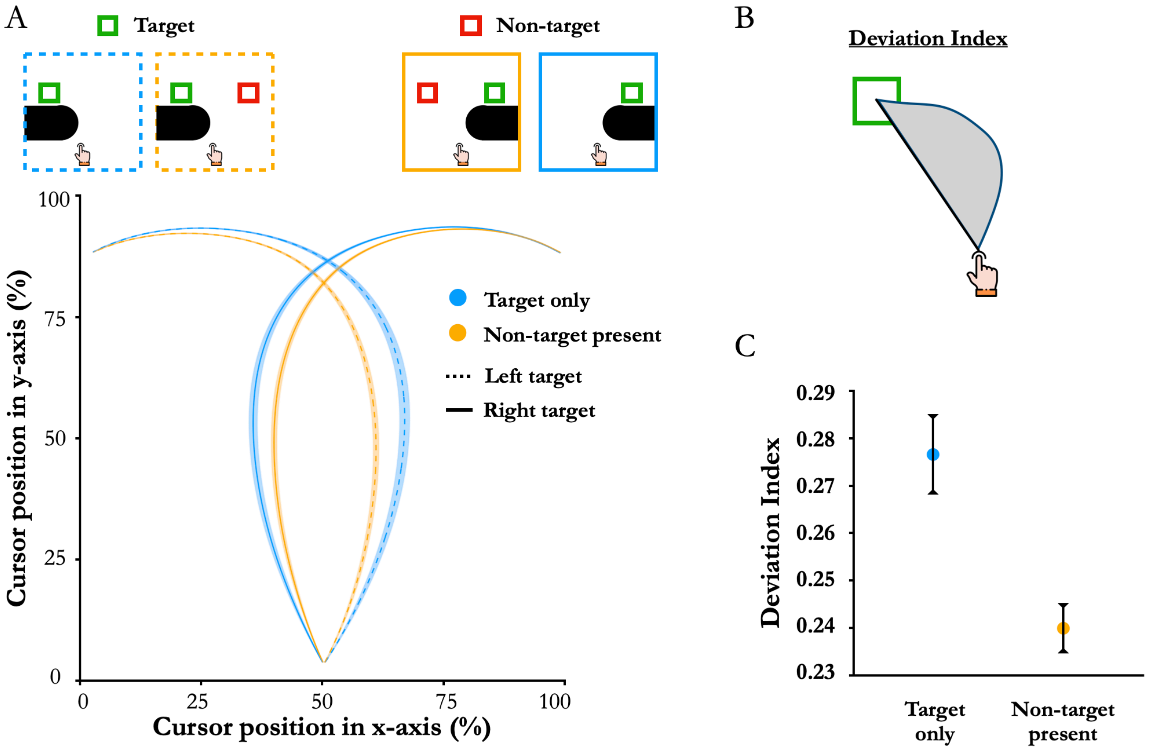

Figure 2: **(A)** Top: In Experiment 1, each trial begins with establishing a visual workspace, including objects (either a green target or a green target with a red non-target), a black obstacle, and the home position (hand icon). Bottom: Participants moved their cursor to the green target. Their movement trajectories were averaged for each of four trial types shown in the top panel. When a non-target appeared in the workspace, the trajectories (orange curves) were repelled relative to the target-only condition (blue curves). The shaded area depict ± 1 SEM of trajectories in the horizontal dimension. **(B)** Schematic of our primary index measuring the deviation of trajectories — the area between the trajectory and a straight line drawn between the start point and the goal. **(C)** The deviation index collapsed over the left and right target conditions, showing that the deviation was significantly smaller when a non-target was present. Error bars depict ± 1 SEM of the mean deviation index for each condition.

condition). In the other half of trials, a non-target (a red square) was also present, positioned at the location symmetric to the target about the vertical midline of the workspace (Non-target Present condition). The barrier prevented participants from reaching to the target in a straight path, inducing them to make curved movements (curved movements were induced because they were a key aspect of our later imitation experiments). After participants clicked the start button at the bottom, their mouse cursor would appear as a yellow disc at the center of the start button, cuing them to move the cursor into the green square while avoiding the black barrier (no movement time criteria was applied). During movements, if the cursor touched or crossed the black region, the trial would be aborted. Successful movements of the cursor into the green target turned the target yellow and initiated the next trial. Participants' full movement trajectories (i.e., x-, y-coordinates of the mouse position) were recorded.

Analysis

To average multiple trajectories made in the same condition, movement trajectories were resampled into 1000 consecutive points at uniform intervals using linear interpolation. The workspace was normalized from 0% to 100% along the x and y axes. Movement trajectories were averaged per participant and then across the group for visualization.

Our primary interest was the spatial deviation of participants trajectories in the Target Only versus Non-target Present conditions. To quantify this deviation, we computed the area between each movement trajectory and a straight line trajectory from the start to the endpoint of the movement, which reflects movement curvature (Figure 2B). In addition to this primary index, we also preregistered secondary analyses using two other metrics — the length of the trajectory (i.e., how many pixels the mouse traveled on the screen per movement) and the maximum deviation away from the straight-line trajectory (i.e., the largest distance between the movement trajectory and the straight path). These indices have been previously used in mouse-tracking studies to assess the curvature of movements (e.g., Freeman and Ambady, 2010; Freeman et al., 2008).

Results

In accordance with our pre-registered exclusion criteria, one subject was excluded for failing to submit a complete data set, leaving 99 participants with analysable data.

Figure 2A shows average movement trajectories across the four trial types. As can be seen here, the presence of the non-target strongly repelled movements, regardless of the location of the target. A paired t-test confirmed that the degree of trajectory deviation (i.e., the deviation index; the grey area schematized in Figure 2B) significantly differed between the Target Only condition and the Non-target Present condition, $t(98) = 8.26$, $p = 6.96 \times 10^{-13}$, $d = 0.83$, $SE = 0.0044$, $CI_{repulsion} = 0.037[0.028, 0.045]$ (Figure 2C). This distractor-driven deviation of trajectories can also be seen in the secondary analyses on the total length of trajectories ($t(98) = 8.06$, $p = 1.89 \times 10^{-12}$, $d = 0.81$, $SE = 3.15$, $CI_{repulsion} = 25.36[19.19, 31.52]$) and the maximum deviation ($t(98) = 9.63$, $p = 7.85 \times 10^{-16}$, $d = 0.96$, $SE = 1.59$, $CI_{repulsion} = 15.34[12.22, 18.46]$), both reported here in absolute pixels.

The repulsion effect robustly emerged in all three preregistered metrics, suggesting that when participants make curved, goal-directed movements in our task, the presence of a non-target exerted a repelling effect. This replication of previous studies establishes that significant non-target interference effects are present when curved movements are made in the visual workspace of our task.

Experiments 2: Distractor effects on imitated movements

In Experiment 2 we begin to address our main question: do non-target effects persist in imitated movement trajectories, when the goal of movements is not to select a target but to produce a specific kinematic profile? We instructed participants to view how another agent moves their mouse to a target, and then imitate the movement they just viewed to the best of their ability.

Method

Participants

One hundred participants were recruited from Prolific. Considering the similar nature of Experiments 2-5, we consistently preregistered this same sample size for each of the experiments.

Stimuli

Ten videos were generated and used in the encoding phases of the task. Each video depicts a yellow disc following a curved path to a green target in the workspace. Five paths terminated at the top-left location in the workspace, and the other five paths were mirror reflections about the midline, ending at the top-right target (See Figure 3B for the workspace and the 10 movement paths that participants viewed). The 10 demonstrated movements varied subtly in curvature but always began at the same point and ended at the green target. The demonstrated movements accelerated such that their trajectory had a bell-shaped velocity profile, making the movement

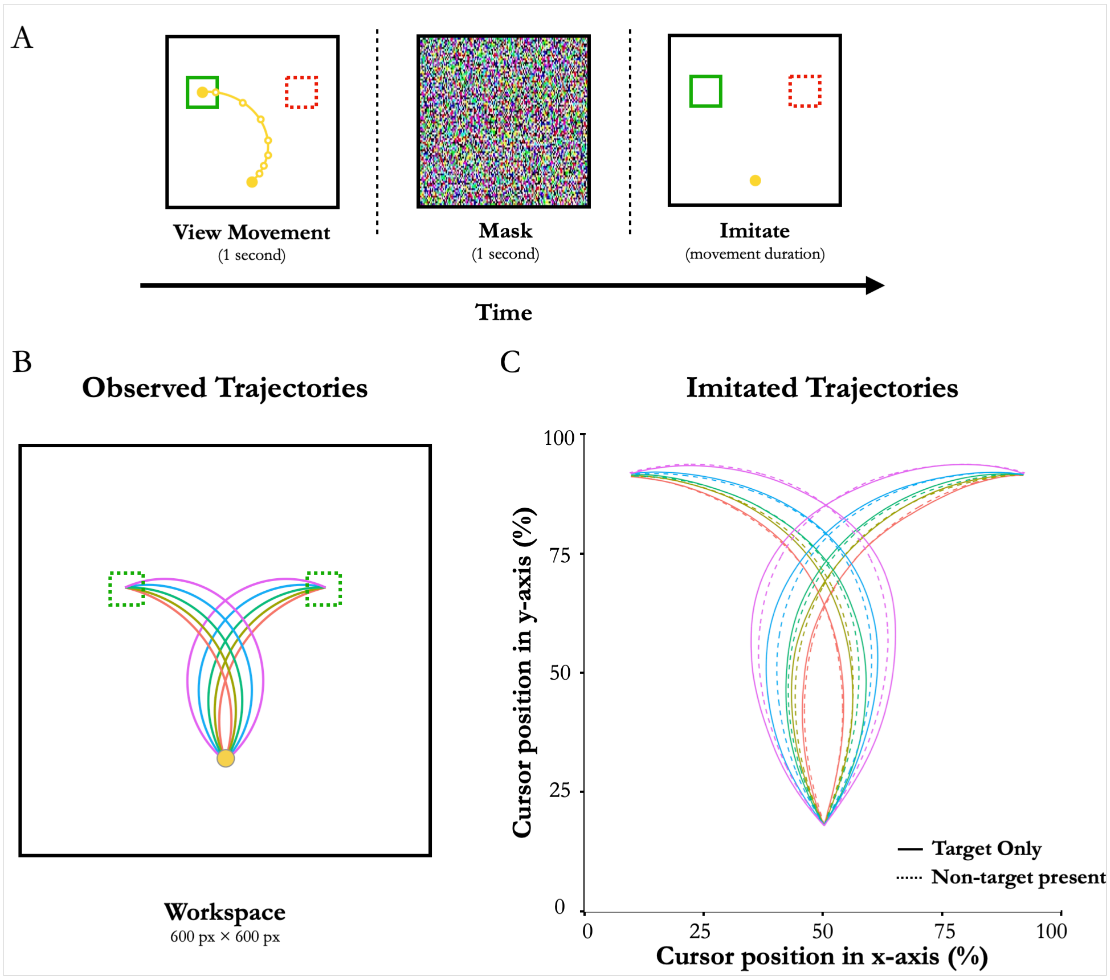

Figure 3: **(A)** Illustration of the imitation task in Experiment 2. Each trial begins with a 1-second video showing an agent's cursor movement. After a 1-second visual mask, participants see the same scene with either only the target present (green box), or both the target and a non-target present (red box), and are asked to click a start button and then reproduce the movement trajectory they just viewed. **(B)** A scaled-down visualization of the workspace showing the observed trajectories used in Experiments 2-5. Ten observed trajectories varied in their curvature (yellow dotted line), ending either in the upper left or upper right target regions (green dotted boxes). **(C)** A visualization of the imitations of ten observed trajectories averaged across participants. The observed trajectories and the imitated trajectories were clearly correlated, suggesting participants effectively encoded and reproduced different movements.

appear natural. Indeed, participants were told that the demonstration movements were actual recordings of other participants' actions. Each demonstrated movement lasted for 1 second from the start of the movement to its landing on the target.

Procedure

On each trial, participants first viewed a video showing an agent move their mouse to a target, and, following this encoding phase, the workspace was visually masked for 1 second. Next, the mask was removed and participants were instructed to click the start position and then move their own mouse (a yellow cursor, same as Experiment 1) to replicate the curved trajectory that they had observed (Figure 3A). Participants performed imitated movements with no time pressure, and were told to be as spatially accurate in their imitated curved movements as possible.

They key manipulation in this task is that an identical set of trajectories were presented in Target Only trials and Non-target Present trials. Each of the 10 demonstrated movement trajectories appeared in both conditions (Target Only vs. Non-target Present), and each unique trial repeated 4 times in the task, resulting in 80 trials total.

Results

One participant was excluded for failing to submit a complete data set, leaving 99 participants for analyses.

As can be seen in Figure 3B-C, the imitated trajectories reflected the true pattern of the observed trajectories, suggesting that participants truly reproduced the observed movements rather than simply reaching to the target [1]. The averaged imitated movement trajectories across the two conditions diverged significantly — the presence of a non-target repelled imitated movement trajectories relative to when a non-target was not present. Examining the curvature of the reproduced trajectories, we found a significant difference in the deviation index between Target Only and Non-target Present conditions, $t(98) = 4.98$, $p = 2.69 \times 10^{-6}$, $d = 0.50$, $SE = 0.0016$, $CI_{repulsion} = 0.0078[0.0048, 0.011]$ (Figure 2C). This difference was confirmed by the other two metrics, max deviation ($t(98) = 2.97$, $p < 0.01$, $d = 0.30$, $SE = 0.65$,

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[1] To assess whether the curvature of imitated trajectories monotonically increases as the five types of observed trajectories (collapsing left and right target), we conducted a one-way ANOVA. The results of the ANOVA showed a significant effect of Observed Trajectory Type on imitated trajectory curvature (i.e., max deviation), $F(1, 493) = 532.6$, $p < 2 \times 10^{-16}$. A linear contrast analysis indicated a significant positive linear trend, $\beta = 11.49$, $t(493) = 23.08$, $p < 2 \times 10^{-16}$. Note that this analysis was not pre-registered. In Experiments 3-5, the reproduced trajectories also saliently reflected the varied deviations in observed movements.

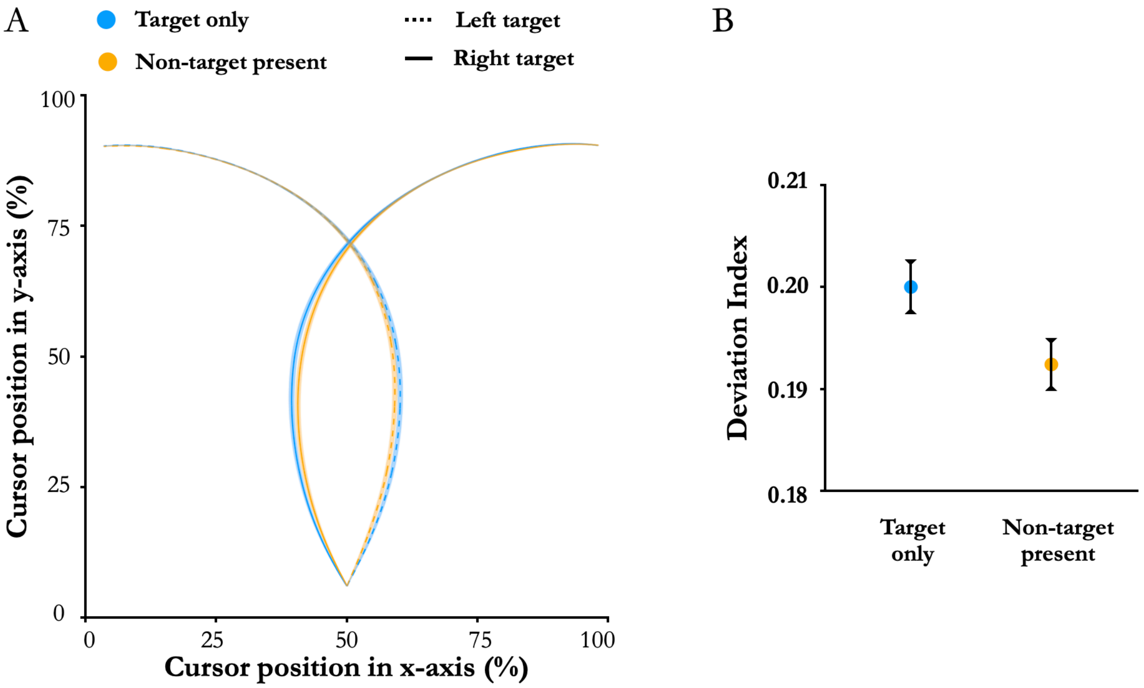

Figure 4: Results of Experiment 2. **(A)** The averaged movement trajectories made in four conditions. The presence of a non-target repels the trajectory away. **(B)** Trajectory deviation significantly differed between Target Only and Distractor Present conditions ($p = 2.69 \times 10^{-6}$). Error bars depict ± 1 SEM of the mean of each condition.

$CI_{repulsion} = 1.96[0.66, 3.25]$) and path length ($t(98) = 2.59$, $p = 0.011$, $d = 0.26$, $SE = 2.33$, $CI_{repulsion} = 6.06[1.48, 10.64]$). Thus, trajectories imitated in the presence of a distracting item deviated less from a straight path and became shorter in length.

Note that the repulsion effects found here were much weaker than in Experiment 1. However, it is not easy to compare these effects across the two experiments given the rather dramatic task differences (e.g., in Experiment 1 participants decide on their own reach trajectory, while in Experiment 2 they are told how to move; a large barrier was present in Experiment 1 but not Experiment 2; etc.). We return to these differences in the Discussion. Nevertheless, the results of Experiment 2 provide initial support for the hypothesis that non-targets automatically affect movement trajectories even when target selection is not the relevant task goal.

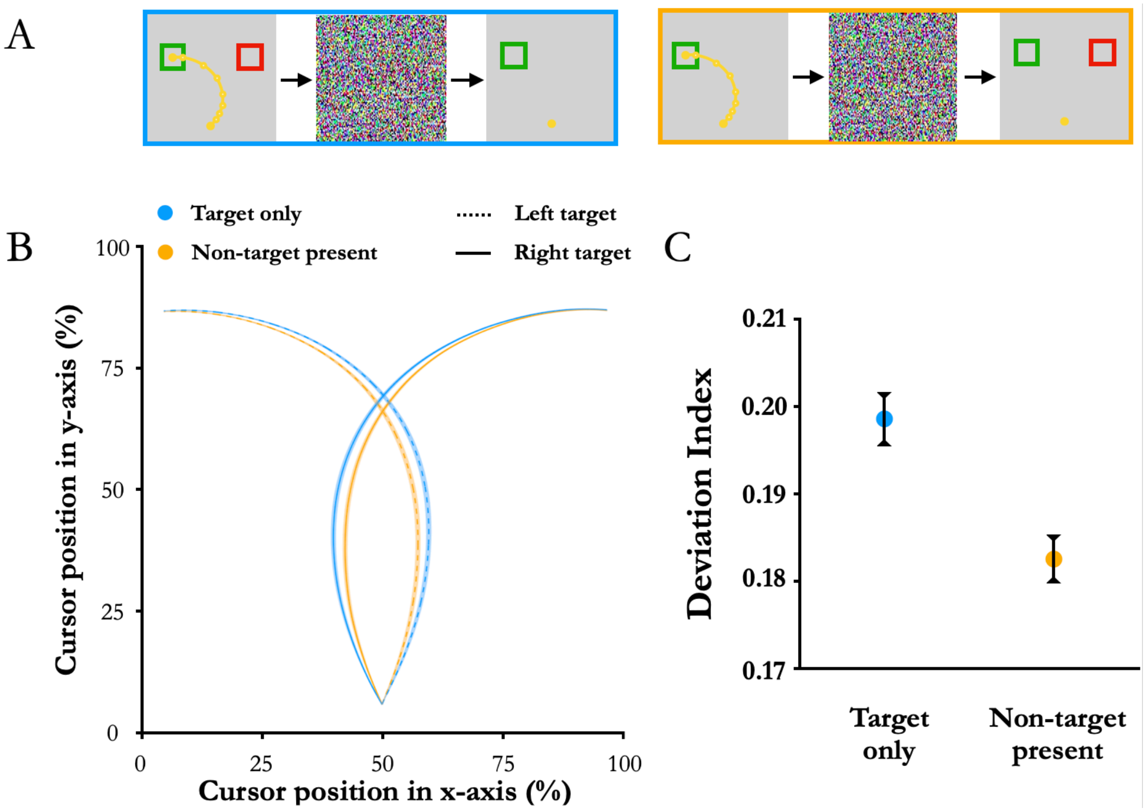

Figure 5: Experimental design and results of Experiment 3. **(A)** In the experiment, participants either view a movement trajectory with a non-target and then reproduce it without a non-target (blue box), or vice versa (orange box). **(B)** The presence of a non-target in imitation phase repels the trajectory away from it. **(C)** The deviation degree significantly differed between Target Only and Non-target Present condition ($p = 3.31 \times 10^{-15}$).

Experiment 3: Effects of encoding context

Experiment 2 revealed robust non-target repulsion effects in imitated movements. However, these effects could perhaps be explained by memory biases formed during encoding of the demonstrated movements. That is, imitated actions may have not been affected by non-targets being present during the imitation phase, but rather, the non-target's presence during initial encoding. To control for encoding effects, in Experiment 3 participants viewed and imitated movements in incongruent contexts: the distractor appeared either in the encoding phase or the imitation phase, but never in both.

Method

One hundred participants were recruited for this experiment from Prolific. The critical difference between this experiment and the previous experiment is that the encoding phase and the imitation phase had an incongruent number of visual objects: Participants viewed videos of movement trajectories in a target-only scene and then were asked to imitate the trajectory with a non-target present with the target, or vice versa (Figure 5A).

Results

Three participants were excluded for failing to submit a complete data set, leaving 97 participants for analyses.

Again, the presence of a non-target in the workspace significantly repelled imitated movement trajectories, replicating the effects of Experiment 2: The repulsion effect was observed when the non-target appeared during imitation but not during encoding (Figure 5B). Thus, even if a movement was first viewed without a second item in the workspace, a non-target being present during imitation repelled movements away. Comparing the two conditions, the trajectories reproduced in Target Only conditions were less deviant then trajectories reproduced when a non-target was present (Figure 5B and C), $t(96) = 9.37$, $p = 3.31 \times 10^{-15}$, $d = 0.95$, $SE = 0.0017$, $CI_{repulsion} = 0.016[0.013, 0.019]$. The comparisons using the other two metrics were also significant (path length: $t(96) = 3.50$, $p < 0.001$, $d = 0.36$, $SE = 2.22$, $CI_{repulsion} = 7.77[3.42, 12.11]$; and max deviation: $t(96) = 7.91$, $p = 4.31 \times 10^{-12}$, $d = 0.80$, $SE = 0.82$, $CI_{repulsion} = 6.52[4.91, 8.14]$).

The results of Experiment 3 suggest that repulsion effects in imitated actions cannot be explained away by encoding processes during the viewing of movement demonstrations.

Experiment 4: Encoding without a goal

In the previous experiment, the encoding scene and the imitation scene were always incongruent, which raised a concern that the repulsion effects we observed in imitation could be framed as attraction effects biased by encoding. That is, observing actions with a salient goal present may have biased subjects to interpret the viewed trajectories as resulting from a target-selection decision process. Here we performed a more dramatic test of encoding effects by fully removing any goal target from the encoding phase. In Experiment 4 participants observed mouse movements on a blank canvas, and then imitated trajectories in one- vs. two-object scenes.

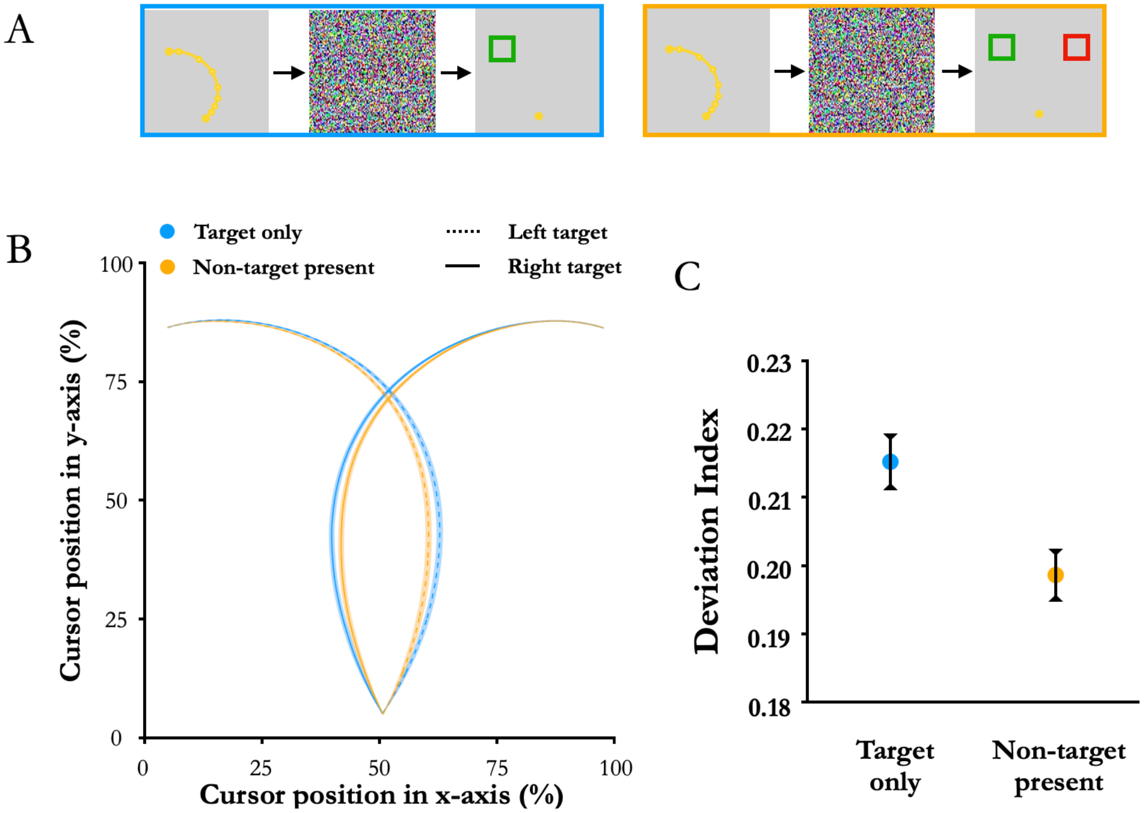

Figure 6: Experimental design and results of Experiment 4. **(A)** In the experiment, participants view a movement trajectory without any objects, and then imitate it in either Target Only scene (blue box) or Non-target Present scene (orange box). **(B)** The presence of a non-target in imitation phase repels the trajectory away from it. **(C)** The deviation degree significantly differed between Target Only and Non-target Present condition ($p = 1.17 \times 10^{-8}$).

Method

One hundred participants were recruited for this experiment from Prolific. The key feature of this experiment is that there were no visual objects (either a target square or non-target square) in the encoding phase. Participants only saw a mouse cursor travel along a curved path that ended either at the top left or top right of the workspace. Objects only appeared during the imitation phase. The same set of trajectories used in Experiment 2-3 were used here, and imitated by participants in Target Only and Non-target Present conditions (Figure 6A).

Results

Again, imitated movement trajectories were repelled away by the simple presence of a non-target in the imitation phase, as can be seen in Figure 6B. Here, participants (N = 100) viewed how the mouse moved in the absence of any goal objects. However, when they attempted to reproduced the curved movements, movements were affected differently by the different imitation environments: Trajectories deviated less when a non-target was present, $t(99) = 6.22$, $p = 1.17 \times 10^{-8}$, $d = 0.62$, $SE = 0.0020$, $CI_{repulsion} = 0.012[0.0083, 0.016]$. The significant difference between conditions also emerged in the max deviation metric, $t(99) = 4.20$, $p = 5.79 \times 10^{-5}$, $d = 0.42$, $SE = 0.81$, $CI_{repulsion} = 3.39[1.81, 4.97]$, though was not seen in total length of trajectory , $t(99) = 6.22$, $p = 0.64$. These results provided further evidence that the repulsion effects of distractors on movements can persist even when goal selection is not relevant to the task.

Experiment 5: Eliminating goal uncertainty

Experiment 2-4 consistently revealed non-target repulsion effects in imitated movements, wherein no selection and little uncertainty was involved in the task. However, across all experimental trials, the direction and the end of movement could be either on the left or right of the workspace, introducing a subtle degree of goal uncertainty. Did this residual goal uncertainty drive the observed non-target repulsion effects? In Experiment 5 we asked whether distractor effects still emerge when no goal uncertainty is present.

Method

One hundred participants were recruited for this experiment from Prolific. The critical difference between this experiment and the previous experiment is that the trajectories that each participant was asked to imitate always terminated in the exact

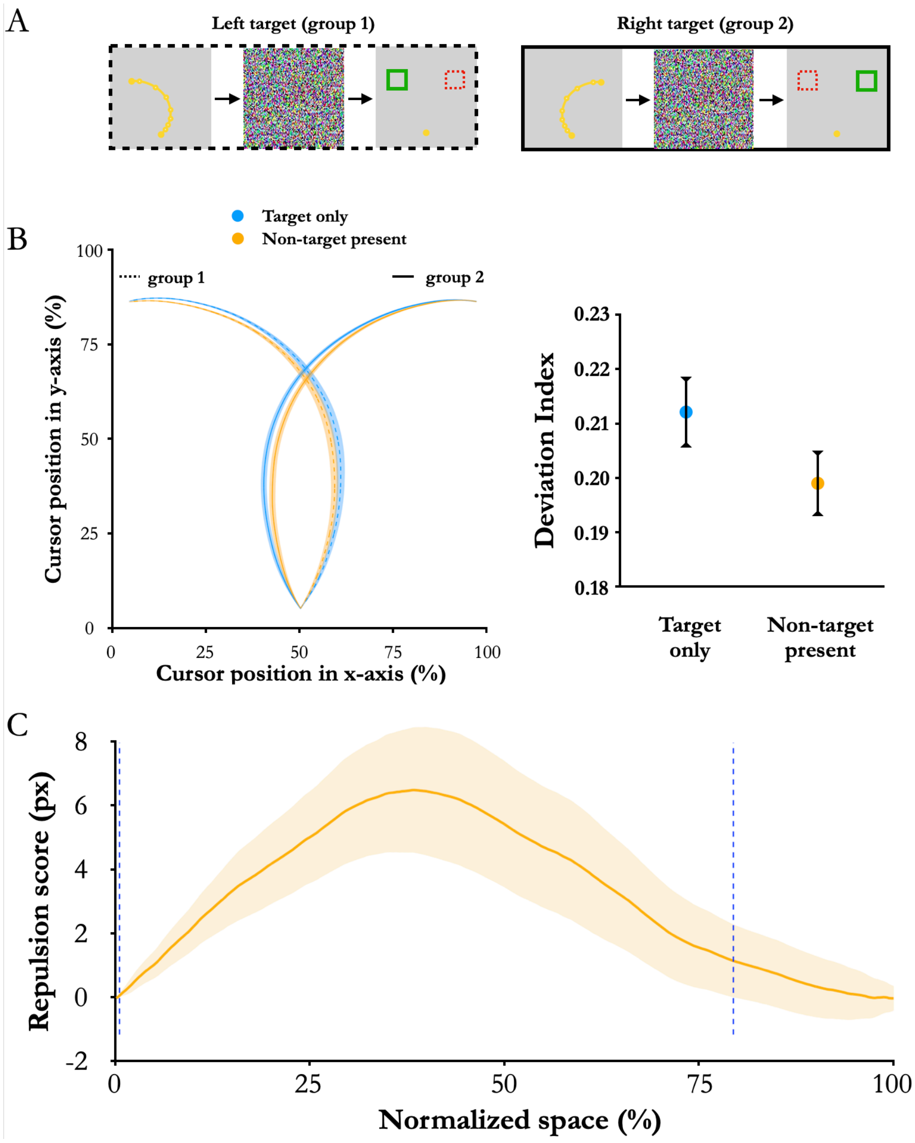

Figure 7: Experimental design and results of Experiment 5. **(A)** In the experiment, participants are divided into two groups; for each group, all observed movements ended at the same location in the workspace on every trial. **(B)** There was a significant difference in trajectory deviation between Target Only and Non-target Present conditions, with non-targets again repelling hand movements away ($p = 1.50 \times 10^{-6}$). **(C)** A repulsion score was computed as the difference along the x-axis between Target Only trajectories and Non-target Present trajectories, thus measuring the strength of non-target repelling effect across the entire resampled movement trajectory. Repulsion scores were averaged across participants at each point. Two blue dotted lines indicate the window where a significant repelling effect is observed (0.5% — 79% of the movements). Shaded band depicts the 95% confidence interval.

same position. That is, for a given participant, the end point of every observed movement and every imitated movement was identical. If the goal uncertainty brought on by having two potential target locations drove our previously observed repulsion effects (Experiments 2-4), in this new experiment those effects should disappear.

At the beginning of the experiment, each participant was randomly assigned to the Left Target Group (group 1) or the Right Target Group (group 2). In the encoding phases, participants viewed and imitated 5 movement trajectories that always terminated at the designated left or right end point (Figure 7A). The imitation phase occurred as either the Target Only or Non-target Present condition. Each unique trial type repeated 4 times, resulting in 40 trials in total.

Results

Three participants were excluded for failing to submit a complete data set, leaving 97 participants for analysis.

As can be seen in Figure 7B, similar movement patterns emerged again: When participants imitated movements with a non-target, their movement trajectory deviated away from the non-target. Note that the target had never changed its location in the task, meaning that participants reached to the same target (and encoded demonstrated movements toward that same target) across all trials. Thus, even with the level of goal uncertainty minimized to essentially zero, the occasional presence of a non-target still interfered with participants' imitated movements: The deviation was again smaller when a non-target appeared opposite the fixed target, $t(96) = 5.13$, $p = 1.50 \times 10^{-6}$, $d = 0.52$, $SE = 0.0025$, $CI_{repulsion} = 0.013[0.0081, 0.018]$. This distractor-induced difference reached significance in one of the secondary metrics (max deviation: $t(96) = 4.39$, $p = 2.91 \times 10^{-5}$, $d = 0.42$, $SE = 1.10$, $CI_{repulsion} = 4.85[2.68, 7.01]$; trajectory length, $t(96) = 1.14$, $p = 0.25$).

This experiment showed non-target repulsion effects in a highly certain context, wherein participants never had to select movement targets in any sense, nor alter their movement targets across trials. These results point to an obligatory, bottom-up inhibitory mechanism whereby visual non-targets may influence the kinematics of a wide range of volitional actions, even imitated ones.

Exploratory analysis

Do the non-target effects we observed bias movements during a motor planning stage or a motor execution stage? To address this question we explored the time course of the non-target repulsion effects. We computed a repulsion score —– the difference in normalized x-coordinates between Target Only and Non-target Present conditions (i.e., the difference between blue and orange curves along the x-axis in

Figure 7B) —– through all the points along the imitated trajectories in Experiment 5.

Significant repulsion effects appeared almost immediately: we observed repulsion biases that exceeded the 95% confidence interval of the repulsion scores as early as 0.5% into the movement trajectory. The effect persisted through 79% of the trajectory (Figure 7C). These results suggest that distractors automatically affect imitated hand movements during motor planning.

General Discussion

Across five experiments, we found that the simple presence of a visual non-target biases participants' hand movements trajectories, even when such movements were not selected to efficiently reach a goal, but simply to imitate another agent's movement kinematics. These effects were replicated over multiple viewing conditions (Experiments 2-4), and when goal uncertainty was completely removed (Experiment 5). These findings suggest that non-target interference effects are "hard-coded" into action planning and not just a function of goal selection and decision making processes.

Repulsion effects in imitation

Non-target effects have been traditionally studied in spontaneous goal-directed actions, leading to the idea that non-targets interfere with a process of selecting an action that efficiently reaches a goal while inhibiting competing responses. For example, the inhibition of attention to distracting objects can be flexible and specifically tuned to the goal-relevant properties of objects (Tipper et al., 1994); hand movement trajectories are biased towards a distracting cue only when the cue shares visual features with the movement goal (Welsh, 2011). Evidence of this sort supports a more top-down process underlying non-target interference effects, whereby distracting information that competes with the current goal biases movement plans. Classic theories account for distractor-induced movement deviations by positing the "averaging" of potential motor vectors towards target and non-targets (Tipper et al., 2000; Welsh & Elliott, 2004). In this view, repulsion effects are the consequence of an inhibitory mechanism that suppresses motor plans to non-targets while potentiating motor plans to targets (Howard & Tipper, 1997; Tipper et al., 1992, 1997).

Our findings here, however, suggest that goal selection is not a necessary condition for non-targets to interfere with actions. Unlike spontaneous movements, imitated movements instead require a mental representation of observed action kinematics, and a subsequent memory retrieval process that drives accurate reproduction. Thus, the focus of imitation is not “where you’re going” but “how you get there” ((Heyes, 2001)). Across several experiments, robust non-target biases persisted in imitated movements of which both the end and the path were predefined for observers. Observers in our imitation tasks did not have to select end goals, conjure their own movement kinematics, nor compute an efficient path to a target — thus, it is not clear how inhibition of competing motor plans would explain our results. Instead, our findings point to a more rigid “automatic policy” of motor planning that avoids non-targets even at the cost of task performance.

Inhibition or avoidance?

Consistent with this idea, the results of Experiment 5 showed that repulsion effects emerged without goal uncertainty and at a very early stage of imitated movement, suggesting an automatic influence on motor planning. Can these effects be explained via visual attention? We do not think so — if anything, attention attracted by a non-target object during the imitation phase, which requires subjects to attend to the kinematics of their hand movements, should pull movement trajectories towards, instead of away from the non-target (Chang and Abrams, 2004; Chieffi et al., 2001; Song and Nakayama, 2006; Welsh, 2011; for a review, see Song, 2019; for evidence that processing hand movements does not demand attention resources, see Reichenbach et al., 2014).

Another possible explanation is that a sophisticated system of obstacle avoidance may exist to maximize the distance between the hand and any possible object collisions. This sort of action-oriented “object field” could induce high sensitivity to visible objects in the workspace, especially those objects close to a planned movement path, and automatically drive movement trajectories away from those objects. Previous studies on reaching present evidence for this kind of avoidance computation (Chapman & Goodale, 2008; Mon-Williams et al., 2001; Rice et al., 2006; Tresilian, 1998). Our results thus could be seen as emphasizing the automaticity of this avoidance system, by showing that it functions even in imitated movements. Though the present work does not dissociate these two mechanisms (competing motor plan inhibition and automatic obstacle avoidance), future work may investigate this further.

Limitations

Our study has several limitations. First, the imitated actions in our study were relatively simple, requiring short hand movements over a small space with a simple curvature profile. Generalizing these results to more naturalistic movement imitation, perhaps involving more complex movements using multiple effectors (e.g., hand gestures), would be a useful topic for future experiments. Second, we did have some shared features in our target and non-target stimuli, like their vertical location and shape (squares). It would be interesting to examine how visual features of targets versus non-targets may influence imitated movements.

Third, we observed a rather large repulsion effect size reduction when going from our non-imitation task (Experiment 1) to our imitation tasks (Experiments 2-5). Aside from large differences in the task goals and workspace visuals, there may be more theoretically relevant explanations for this reduction. For example, it may be that non-target effects are amplified when agents have to form their own movement plans from scratch rather than trying to match a template in (visual or motor) working memory (Hillman et al., 2024). Or perhaps there are multiple underlying causes of non-target biases, with separable effects related to goal selection and inhibition versus automatic obstacle processing.

Closing remarks: Representing non-targets in motor planning

We perform movements in a variety of cluttered scenes, and skilled motor control requires efficient processing of complex visual input. Though it has been thought that visual non-targets primarily bias movement planning through a goal selection process, our results here suggest that non-target interference effects can also appear without demands to select targets or optimize movement efficiency. This study also adds to a large body of previous literature demonstrating tight links between seeing and acting. Visuomotor processes may integrate environmental information into motor planning through an automatic and obligatory mechanism, such that non-target objects are "baked-in" to volitional motor plans.

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