Attention, Perception, & Psychophysics
https://doi.org/10.3758/s13414-021-02291-4

SHORT REPORT

Multiple-object tracking and visually guided touch

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Accepted: 21 February 2021

Abstract

Multiple-object tracking (MOT) involves keeping track of the positions of multiple independent target items as they move among distractors. According to Pylyshyn (*Cognition, 80,* 127–158, 2001), the item individuation mechanism used in MOT is also used in visually guided touch. To test this, we compared single-task MOT (MOT alone) with dual-task MOT (MOT while touching items that changed colour), looking for interference: cases where single-task performance was worse than dual-task. Touching items that changed colour interfered with MOT, but effects varied depending on whether the item touched was a target or distractor in MOT. Touching distractors always reduced MOT performance more than touching targets. Touching targets during MOT did not interfere when there was only a single target to track but interfered more once there were two or more targets. We also measured interference based on latencies to touch items that changed colour, comparing single and dual-task conditions (touch alone, touch + track). MOT interfered with touch, increasing RT to touch items that changed colour, with latencies significantly higher when those items were distractors rather than targets. Overall, there was *general interference* (differences between single and dual-task performance), as might be expected if coordinating the two tasks required a common limited resource such as general attention or working memory. However, there was also *differential interference* that varied based on whether the touched item was a target or distractor in MOT. This differential interference suggests the specific mechanisms used in MOT may also play a role in visually guided touch.

Keywords Multiple-object tracking · Exogenous orienting · Premotor theory of attention · Selection for action · Attentional tracking

Coordinated action frequently requires tracking the positions of multiple objects as they move among others. Pylyshyn and Storm (1988) developed the multiple-object tracking (MOT) task to measure this perceptual ability. Although the mechanisms behind MOT are thought to be fundamental to touching moving items (e.g., Pylyshyn, 2001), the relationship between MOT and visually guided touch is still unclear. In this study, we investigate how MOT is affected by exogenously directed touch in a series of experiments in which item-colour changes were used to signal the items to be touched.

In their studies of MOT, Pylyshyn and Storm (1988) found that young adults were capable of tracking 3–5 targets at once, even when the objects were moving too rapidly and erratically to move the eyes or attentional focus from target to target to update item positions. Since then, MOT has been investigated in many labs (see Meyerhoff et al., 2017, for a review), and it represents an interesting test case for theories of attention. MOT involves selective attention in that some items are selected as targets while others are not, but in MOT, selection has to be object-based rather than location-based because items move. Furthermore, though early theories of attention assumed that attentional selection could only apply to one target item/location at a time, MOT performance is better than would be expected if participants were moving a singular attentional focus from target to target. Although the allocation of attention is often associated with foveating eye movements toward targets, in MOT, participants tend to fixate on central locations rather than individual targets (Fehd & Seiffert, 2008).

Nonetheless, if MOT is to be useful in daily life, it is important to understand how selection in MOT is employed to direct action. There are several theories about the relationship between selective attention and action, but the most dramatic is premotor theory (e.g., Rizzolatti et al., 1987). According to

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Published online: 30 March 2021

this theory, all attentional selection is selection for action. If that is true, it is possible that even tasks that require reporting the identity of an item rather than directing an action toward it could involve forming an action plan for how to touch that specific item among others (a premotor plan). It is important to note that a critical component of any such plan would have to be item location. Although this research on action plans was initially developed with single items in mind, Gallivan et al. (2011) examined reach trajectories and concluded that unconscious action plans may be formed for up to four individuated items at once in a visual scene. If selecting an item as a target involves creating an action plan, and if this action plan updates as items move, then in a MOT task with four targets, there would be four developing premotor plans, one for each target. Importantly, there would be no corresponding plans for distractors as they are not selected/attended in the task. With this in mind, if participants were required to touch any of the items that changed colour during MOT, touch latencies should be faster for targets than distractors because the targets would already be individuated and localized for purposes of the MOT task. As a result, there would already be developing premotor plans containing localization information for the targets.

Differences between target and distractor touch conditions should also be evident in terms of the percentage of correctly reported targets at the end of the MOT trial. If directing an action toward a moving item is both necessary and sufficient to shift attention to that item, as suggested by premotor theory (Rizzolatti et al., 1987), then touching a moving item during the tracking interval (before the final report) would cause it to be selected. Evidence suggests that for any given speed of item movement there seems to be limits in the number of targets that can be selected and thus tracked at once. If touching a distractor causes the distractor to be selected, then touching a distractor could displace the selection from a target, reducing the number of correctly reported targets at the end of the tracking trial. Though touching moving items during MOT constitutes a secondary task that could produce general interference, perhaps due to competition for general working memory resources or whatever is necessary to "pay attention" (e.g., Allen et al., 2006; Kunar et al., 2008; Trick et al., 2006), touching targets should interfere less than touching distractors. Touching targets may even benefit performance if it causes the reselection of a target that had been "lost" during item movement. In fact, it is possible that even if the targets are not yet lost, touching one may somehow serve to reinforce selection, increasing the resources devoted to that target (e.g., Alvarez & Franconeri, 2007; Thornton et al., 2014). This means that the identity of the item to be touched (whether it is a target or distractor in MOT) is important; there should be *differential interference*.

Pylyshyn (2001) initially proposed a relationship between MOT and visually guided touch, but these ideas were never tested. Instead, it was Thornton and Horowitz (2015; see also Thornton et al., 2014) who performed the first study where participants had to touch moving items that changed colour during MOT. In their 2015 article, Thornton and Horowitz had a MOT task with four targets and four distractors in which individual items changed colour at unpredictable intervals during item motion (five changes over a 30-second tracking interval). They compared single-task MOT—when individual items changed colour, but there was no need to touch them—with performance when participants had to touch the items that changed colours during the tracking interval (the motion phase of the tracking trial).

Thornton and Horowitz (2015) compared MOT performance in trials where items just changed colour (their MOT condition), with performance when participants touched items that changed colour and the items were either all targets in MOT (touch-targets condition) or a mixture of targets and distractors in MOT (touch-all condition). They showed that performance was worse when participants had to touch items that changed during MOT than when the items changed colour but there was no need to touch them. That is, they showed that there was *general interference*, which might be expected if the tasks shared a single common resource such as working memory or general attention. In this, Thornton and Horowitz replicated the results of earlier studies that showed that a variety of different tasks interfere with tracking, including having a cell phone conversation (Kunar et al., 2008), categorizing auditory or visual digits (Allen et al., 2006), or tapping fingers (Allen et al., 2006; Trick et al., 2006).

However, showing that the operations used in MOT are actually part of visually guided touch requires demonstrating *differential interference*: differences in the effects of touching items that changed colour as a function of whether those items are targets as compared with distractors in MOT. The design of the Thornton and Horowitz (2015) study made it impossible to carry out some of the comparisons necessary to show differential interference, because they often combined data from different conditions. For example, their single-task MOT condition mixed together trials where targets and distractor items changed colour. That is a problem because it is important to establish that colour change per se does not affect targets and distractors differently before comparing conditions that require participants to touch targets and distractors that change colour. Colour changes can produce transients, and transients in an image can sometimes cause a reallocation of attention even when there is no need to touch items (e.g., Theeuwes, 1994). In fact, Pylyshyn (2001) argued that such transients might reset the indexing mechanism used in MOT so that the item undergoing change is assigned a FINST (a mental reference token used in tracking an item). If a FINST was reassigned to the item undergoing change, a colour change on a distractor in MOT would be especially damaging because it could cause that distractor to be falsely reported as a target at the end of the trial. Therefore, to investigate the differential effects of touching items that changed colour based on whether they were targets or distractors in MOT, it was important to first demonstrate that there were no differential effects of colour change when there was no need to touch the items. For this reason, in the present study we had two separate change conditions—change target and change distractor—and compared them with each other and standard MOT (where items did not change colour). That way any differences in target change and distractor change conditions could be subtracted out before comparing target touch and distractor touch conditions (where participants touched targets or distractors that changed colour, respectively).

Similarly, although Thornton and Horowitz (2015) had a *touch-target* condition, they did not have the necessary touch distractor condition as a comparison. Instead, they had a *touch-all condition*, which was an average, a mixture of targets and distractors. Not surprisingly, the differences between the touch-target and touch-all conditions, though in the predicted direction, were not large. More dramatic differences might emerge if target and distractor touch conditions were compared directly.

There were other things that we did to modify the methodology to make it more sensitive to differences in performance. Items were moving slowly enough in Thornton and Horowitz (2015) that MOT performance at four targets was close to ceiling ($k = 3.77/4$). A more demanding tracking task would be more likely to produce differences in tracking performance. To make the task more challenging, we increased the speed of item movement (see Alvarez & Franconeri, 2007) and the total number of items in the display (e.g., see Bettencourt & Somers, 2009; Vater et al., 2017).

We also made a slight modification to the methodology to make it easier for participants to keep the display in a stable position throughout the study. In the present study, we placed the iPad on a stand on a desk. That way we could be sure the display would not shift positions as the participants moved to touch items. Thornton and Horowitz (2015) had their participants cradle an iPad in their left hands (with the fingers of their left hands grasping the farthest edge of the iPad) while touching items that changed colour with the index fingers of their right hands. With this arrangement, it is possible that there could be moment-to-moment changes in the position of the display that might contribute to variability in response.

We also wanted to increase the scope of the study. Thornton and Horowitz (2015) restricted their investigation to trials where there were four targets. However, it would be useful see how the effects of visually guided touch change with increases in the number of targets to be tracked at once. Tracking performance is typically very good when there is only a single target (e.g., Trick et al., 2006), but an analysis of single-target performance may be especially revealing when studying the effects of visually guided touch. When participants carry out two tasks at the same time, interference is to be expected; this interference presumably reflects the working memory demands of coordinating the two tasks. However, what would happen if there was only a single target to track and participants had to repeatedly touch that target during MOT? It is possible that even though the items changed positions from moment to moment as they moved, repeatedly touching the same item might reduce the demands of the touch task to such an extent that there would no longer be interference between MOT and visually guided touch.

In the first studies, we had participants tracking 1–4 targets in displays of 10 items. There were five conditions. Three assessed the effects of colour change per se; we compared performance in a MOT task where items did not change colour with performance where targets or distractors in MOT changed colour during the item movement phase of the trial (the standard MOT, target change, and distractor change conditions, respectively). The other two conditions involved trials where participants had to touch MOT targets or distractors that changed colour during item movement (target change + touch, distractor change + touch).

In all studies, dual-task interference was defined as the difference in performance between the change condition and the corresponding change + touch condition. Our primary prediction was that there would be differential interference, which is to say that the identity of the item to be touched (target as compared with distractor in MOT) would have an effect on how much dual-task interference occurred. In terms of MOT accuracy (the percentage of correctly identified targets), we predicted the difference between change and change + touch conditions would be larger for distractors than targets in MOT. Touching distractors should interfere more than touching targets if touching an item necessarily involves shifting attention toward that item, as might be consistent with premotor theory. We also predicted that latencies to touch items that changed colour would be higher when the items were distractors as compared with targets in MOT, as would be expected if the targets had a preexisting action plan while the distractors did not.

To begin, these hypotheses were tested in two parallel experiments that were the same, except for one key difference: the positioning of the index finger in the change + touch conditions. We were concerned that having a set starting and ending point for the finger for each item touch would increase the amount of interference produced by change + touch conditions. To use Pylyshyn's parlance, if there was a set starting and ending point for the index finger, it would also have to have a spatial reference token (a FINST). Thus, every item touch (and there were 2–3 in every tracking interval) would involve two components: moving the index finger to the item that changed colour and then moving the finger back to the designated starting point. Because we did not know whether this would affect the results, we conducted two studies: one where participants were instructed to touch items that changed colour and given no explicit instructions for what to do next, and another where participants were instructed to touch items that changed colour and then return their index fingers to a specific starting point after each touch. (These two experiments are referred to as the supplementary experiment and Experiment 1, respectively.) We predicted that the pattern of the results would be the same in these two studies, though the touch task would produce more interference when participants had to move their fingers back to a fixed starting point between item touches, as occurred in Experiment 1. This suggests that there should be larger differences in MOT performance between the change and change + touch conditions in Experiment 1 than in the supplementary study. As it turns out, the results of the two studies were remarkably similar, and to save journal space, we have only reported Experiment 1 in the body of this paper. The results of the supplementary experiment are available on the Scholars Portal Dataverse page associated with this paper (https://doi.org/10.5683/SP2/WE9TOY).

For all of the studies (Experiment 1, Experiment 2, and the supplementary experiment), a priori power analyses were conducted to estimate the required sample size. We estimated that we would need to test 18–34 participants to have adequate power (p = .80) to identify the effect sizes listed in Thornton and Horowitz (2015). We tested 39 and 37 participants in the supplementary experiment and Experiment 2, respectively, but in Experiment 1 we tested 72 participants. Experiment 1 required a larger sample because one of the touch latency comparisons involved restricting analyses to trials where participants correctly reported the identity of all of the targets in MOT. As the number of targets to be tracked increased to four, there were fewer and fewer participants that had latency data to analyze. Consequently, we tested a larger number of participants in Experiment 1 in the hopes of getting sufficient data for that latency comparison.

Experiment 1

Method

Participants

Seventy-two participants were recruited from the University of Guelph participant pool (49 females, M_{age} = 18.67 years, SE = 0.14 years). All had normal or corrected-to-normal vision. On average, participants reported 2.27 hours a week playing video games (SE = 0.48) and 2.42 hours a week participating in team sports (SE = 0.58).

Design

Participants tracked 1–4 targets in five different conditions: standard MOT, target change, distractor change, target change + touch, distractor change + touch. In the standard MOT and change conditions, participants only had to track targets (single task). Performance in these trials was measured as the percentage of correctly identified targets in the final target report (e.g., 3 targets correct out of 4 would be 75%). In the dual-task conditions, participants had to track the targets and touch any items that changed colour during item motion (the tracking interval). As in the single-task condition, the percentage of correctly identified targets was measured at the end of the trial. However, in the dual-task conditions, we also measured the average latencies to touch items that changed colour in the midst of item movement during the tracking interval, comparing latencies when those items were targets as compared with distractors in MOT. Because there were 2–3 touches in each tracking interval, latencies were averaged across successive touches. Thus, to summarize, this study was designed to address three research questions:

(1) Does colour change in items affect MOT?
(2) Does touching items that change colour interfere with MOT?
(3) Are touch latencies higher for targets than for distractors?

Apparatus and stimuli

All stimuli were presented on an iPad with screen dimensions of 20 × 15 cm and a screen resolution of 1,024 × 768 pixels. Stimuli were displayed within a central black rectangle that subtended approximately 22° × 17° visual angle; during the task the stimuli always remained within this space. The stimuli were white spheres that looked like pearls that were lit from above. These spheres had a diameter of 52 pixels (visual angle of 1.6°).

The current experiments used a touch-based iPad task modified from that of Thornton and Horowitz (2015). The motion duration was decreased from 30 seconds in the original study to 10 seconds in the present study to accommodate a larger number of conditions. Furthermore, to make the task more challenging, item speeds were increased from 2.0° to 4.0° per second, and the total number of items in the display was increased from 8 to 10.

Each trial had four phases: (1) initialization, (2) target assignment, (3) motion (the tracking interval), and (4) target report. At the beginning of each trial, in the *initialization phase*, 10 stationary white spheres were presented in random locations across the tracking field for 3 seconds. Then, during the *target assignment phase,* a random 1–4 of the spheres would flash to indicate that they were targets, changing back and forth from white to pink for 2 seconds. Then, all the spheres became white again for half a second. At this point the *motion phase* began, and the 10 spheres moved randomly and independently of one another for 10 seconds. During the motion phase, the items moved at a base speed of 4.0° per second, changing direction after a path length of about 2.0°. The path length was constrained so that objects always remained within the tracking field. If two items were to collide, they would pass through each other instead of bouncing off each other. After the 10 seconds of motion, the spheres stopped moving. Then, the *target report phase* began. During that phase, participants each used the index finger of their dominant hand to touch the items (spheres) that they believed to be targets in MOT. In the practice trials only, participants were given feedback after they made their response (the targets flashed). A schematic of the trial sequence is shown in Fig. 1.

The conditions varied based on what happened during the motion phase (the tracking interval). In the standard MOT condition, the trial structure followed the four phases described in the previous paragraph; the spheres remained white throughout the motion phase, and there was no need to touch moving items. In contrast, in the change conditions, a sequence of two or three colour changes would occur during the motion phase, with the colour changes occurring 2–3.5 seconds apart. During each colour change, one of the spheres would turn pink for 2 seconds. In the target-change trials, the sphere that changed colour was always selected from one of the targets in the MOT task. Conversely, in the distractor-change trials, the sphere that changed colour was always selected from one of the distractors in the MOT task. Regardless, colour changes would typically not occur twice in a row on the same sphere. The only exceptions to this rule were for trials with a single target in the *target-change* and *target-change + touch* conditions (with only one target, there was only one item that could change colour).

In the two change + touch conditions, participants saw spheres changing colour during the motion phase and had to touch them as quickly as they could. Throughout this paper, when touch latencies are discussed, it refers to the time between when the sphere changed colour (turning pink) and when the participant touched it. Once the participants touched the item, it would turn back to white. If participants did not touch the item within 2 seconds of the colour change, the trial was aborted. As in the colour-change conditions, in a given trial the spheres that changed colour were either all targets or all distractors in MOT. To discourage anticipatory touches, the interval between touches was randomly selected, varying between 2 and 3.5 seconds for each item touch. There were 2–3 item touches per trial and consequently, participants could not predict the specific number of times that they would have to touch items in any given trial.

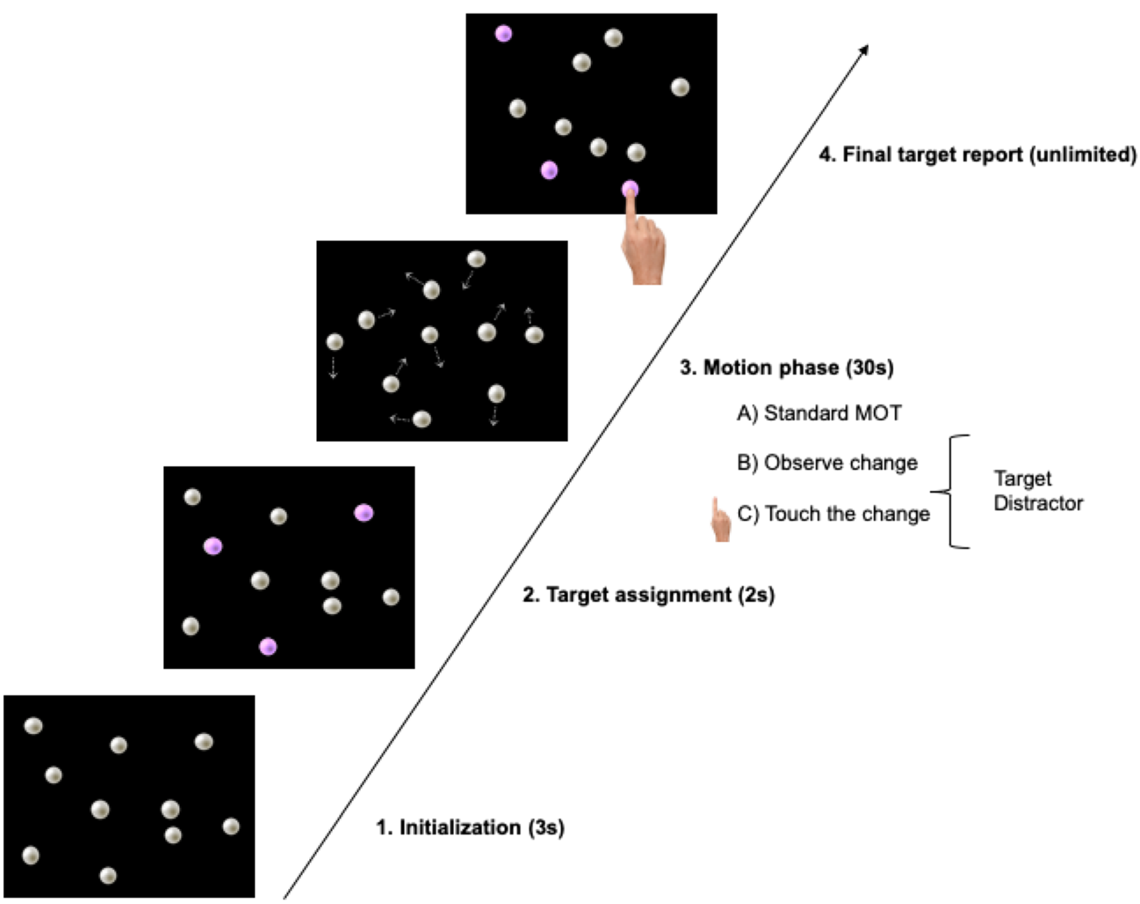

Fig. 1 Multiple-object tracking trial sequence in Experiment 1 (the same sequence as in the supplementary experiment: https://doi.org/10.5683/SP2/WE9TOY, Scholars Portal Dataverse)

Procedure

Participants were seated 50 cm from the display, and the iPad was propped up on the desk in a landscape orientation. Following the consent procedure, participants were given instructions for the MOT task as a whole. They were asked to monitor the positions of spheres that flashed at the start of each trial (the targets) and track them as they moved. Please note that whenever we talk about targets in this paper, we are referring to the items that flashed at the beginning of the trial to indicate they were the targets in MOT during the target assignment phase. At the end of the trial, once item motion stopped, participants identified the items that were targets by touching them with the index finger of their dominant hand. Note that whenever accuracy is mentioned in this paper, it refers to the percentage of accurately reported targets items in MOT.

As is typical in most studies that use the mark-all paradigm for MOT, the paradigm in which all of the targets are reported at the end of each trial (Meyerhoff et al., 2017), we did not analyze the time required to report the positions of the targets. (That time would necessarily increase with the number of targets to be reported.) Instead, participants were allowed to take as much time as they needed to identify the targets in the target-report phase at the end of the trial. Participants were encouraged to guess if they were uncertain. That way the number of answers that they submitted would always be equal to the number of targets they had to track.

Participants completed a total of 160 experimental trials in five conditions (standard MOT, target change, distractor change, target change + touch, distractor change + touch). Change trials for targets and distractors were randomly intermixed in one block; change + touch trials for targets and distractors were randomly intermixed in another. Consequently, there were three different blocks of trials: (1) standard MOT, (2) target and distractor change, and (3) target and distractor change + touch. Participants completed these three blocks in a counterbalanced order. In the single-task blocks, participants only had to report the identity of the targets. In the dual-task conditions (change + touch), participants were instructed to both touch any item that changed colour during item motion and report the identity of the targets in MOT at the end of the trial. Participants were instructed to give equal emphasis to touching moving items that changed colour and reporting the positions of targets in MOT at the end of the trial. For consistency across conditions, participants always positioned the index finger of their dominant hand on a tape line starting point. In the change + touch trials, participants were further instructed to return their finger back to this tape line starting point between item touches (see Fig. 2).

Data were recorded in the experimental trials, with eight trials at each target numerosity (1–4) and trial type (standard MOT, target change, distractor change, target change + touch,

Fig. 2 Experiment 1 setup

distractor change + touch). Thus, there were 32 trials in the standard MOT condition, and these were presented together in a single block (4 target numerosities × 8 trials each). The blocks for the change and change + touch conditions each had 64 trials, with trials involving colour changes in targets and distractors randomly intermixed. Every 32 trials, participants were instructed to look away from the screen to rest their eyes. Immediately before the experimental trials in each block, participants did eight practice trials (two each at each target numerosity in the condition).

Results

The analyses that follow involve repeated-measures analyses of variance (ANOVAs), with the Greenhouse–Geisser correction applied against violations of the sphericity assumption. The Bonferroni correction was applied for post hoc comparisons to account for family-wise error rate. Analyses were performed in two parallel experiments: Experiment 1 (where participants moved their index finger back and forth from a fixed starting point) and the supplementary experiment (when they did not; see https://doi.org/10.5683/SP2/WE9TOY, Scholars Portal Dataverse). The results were remarkably similar, though touch latencies were marginally higher in Experiment 1 than in the supplementary experiment, as might be expected if participants were positioning their hands strategically ($M_{\mathrm{difference}}$ = 95 ms), $F(1, 92) = 3.89$, $p = .052$, $\eta_p^2 = .04$. As well, as predicted, there was more interference in Experiment 1 (a bigger difference between the change and change + touch condition), but this discrepancy in performance was not statistically significant ($M_{\mathrm{difference}}$ = 2.85%), $F(1, 92) = 2.33$, $p = .130$, $\eta_p^2 = .02$.

In Experiment 1, data from four participants were lost due to technical problems. Data from three more participants were dropped because their performance was ~3–5 standard deviations below the mean in the standard MOT task. (This represented a loss of 4.0% of the remaining sample after those dropped due to technical issues.) In the sections below we will address our three research questions: (1) the effects of colour change per se on MOT performance, (2) the effects of touching items that changed colour on MOT, and (3) the effects of the identity of the item (whether it was a target or distractor in MOT) on latencies to touch items that changed colour.

Does colour change in items affect MOT?

To determine whether colour change per se affected tracking performance, we compared standard MOT, where there was no change in item colour during motion, with performance in trials where targets or distractors in MOT changed colour during item motion. The percentage of accurately identified targets in MOT was analyzed as a function of the items that changed colour during item motion (none, targets, distractors) for 1–4 targets (see Fig. 3). Overall, contrary to what might be expected if changes in item colour produced an obligatory reassignment of attention, colour change had little effect on MOT performance, and there were no significant differences between the three conditions, $F(1.80, 113.53) = 2.21$, $p = .120$, $\eta_p^2 = .03$. Although the percentage of accurately identified targets declined with increases in the number of targets, as is typical in tracking studies, $F(2.09, 131.40) = 93.50$, $p < .001$, $\eta_p^2 = .60$, there was no Condition × Number of Targets interaction, $F(5.59, 351.94) = 0.76$, $p = .595$, $\eta_p^2 = .01$.

Analyzing the percentage of correctly identified targets allows us to compare performance across target numerosities because the maximal accuracy (100%) does not vary with the number of targets to be tracked. However, it is easier to interpret results expressed in terms of k, the capacity given the number of targets to track, though the maximal value for k necessarily increases as the number of targets to be tracked increases. Hulleman's (2005) high threshold procedure was used to estimate k and this is reported in Table 1. Generally, in the standard MOT and change trials, participants seemed to be tracking approximately three items at once in the four target conditions. There were no significant differences in k among the standard, target change, and distractor change conditions for 1, 2, 3, or 4 targets (Bonferroni test, $p > .1$ for all).

Does touching items that change colour interfere with MOT?

The percentage of correctly identified targets was analyzed as a function of task load (single task: change alone, dual task: change + touch), the identity of the item that changed colour (target or distractor in MOT), and number of targets to be tracked in MOT (1–4). Results are shown in Fig. 4. Overall, there was evidence of both general interference (task load), $F(1, 63) = 345.70$, $p < .001$, $\eta_p^2 = .85$, and differential interference (Task Load × Item Identity), $F(1, 63) = 169.20$, $p < .001$, $\eta_p^2 = .72$, as well as a three-way interaction (Task Load × Item Identity × Number of Targets), $F(2.96, 186.24) = 8.73$, $p < .001$, $\eta_p^2 = .12$. When participants touched items that changed colour and the items were distractors in MOT, it produced markedly greater reductions in MOT accuracy as compared with when the changing items were targets. All lower order effects were significant, with the exception of the Number of Targets × Task Load interaction, as can be seen from Table 2.

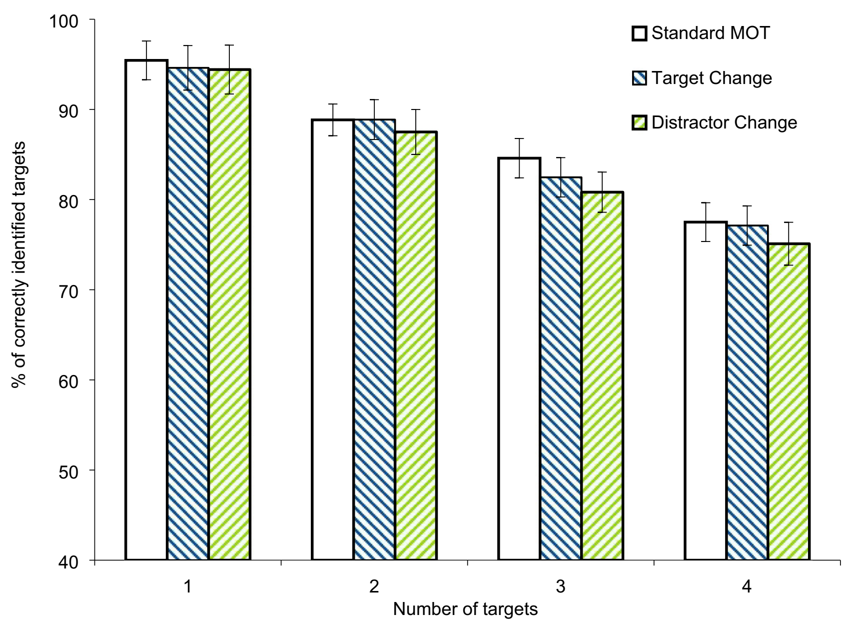

Fig. 3 Experiment 1: Percentage of correctly identified targets in multiple-object tracking (MOT) as a function of the identity of the item that changed colour (standard MOT—no colour change, target in MOT changes colour, distractor in MOT changes colour) and the number of targets to track (1–4). Error bars denote 95% CIs

Table 1 Experiment 1 tracking capacity (k) when participants were required to track 1–4 targets in five conditions: standard multiple-object tracking (MOT), targets in MOT change colour during motion, distractors in MOT change colour during motion, participants touch targets in MOT that change colour during motion, participants touch distractors in MOT that change colour during motion

Number of targets to be tracked	1	2	3	4
Standard MOT	0.95	1.77	2.51	2.94
Target change	0.95	1.77	2.43	2.91
Distractor change	0.94	1.74	2.37	2.81
Target change + touch	0.95	1.61	2.15	2.36
Distractor change + touch	0.69	1.18	1.48	1.46

To simplify interpretation, we focused on interference, calculating the *difference* in MOT performance between single-task (change alone) and dual-task (change + touch) conditions by subtracting dual-task from single-task performance. As can be seen from Fig. 5, there was significantly more interference in the distractor-touch condition than the target-touch condition at all target numerosities (Bonferroni, $p < .001$ for all). Because there were theory-based reasons for expecting differences between targets and distractors, planned comparisons were carried out analyzing the distractor and target touch conditions separately. The amount of interference produced by touching distractor items that changed colour did not vary with the number of targets that the participants were tracking, $F(2.88, 178.72) = 1.73$, $p = .165$, $\eta_p^2 = .02$. In contrast, the amount of interference produced by touching target items that changed colour varied significantly with the number of targets, $F(2.87, 177.25) = 9.69$, $p < .001$, $\eta_p^2 = .10$.

The condition where there was only a single target was special because in the target change + touch condition, that meant that participants would be obligated to repeatedly touch the same item 2–3 times during each tracking interval. As can be seen from Fig. 5, there was no interference between visually guided touch and MOT when tracking one target in the target change + touch condition. In addition, there was significantly less interference when tracking one target in the target change + touch condition than in any of the other conditions (Bonferroni, $p < .001$). In fact, when there was only a single target in the target change + touch condition, dual-task performance was slightly (though nonsignificantly) better than single-task performance.

Table 3 presents the analyses in terms of k, tracking capacity. This table shows that at almost every target numerosity, there was a significant difference between the change and change + touch conditions for both targets and distractors. The only exception was the special case where participant tracked one target and the changing item was a target in MOT (Bonferroni, $p < .05$). This demonstrates that there was significant interference between visually guided touch and MOT in almost every condition and number of targets. Moreover, Table 3 shows that at every target numerosity, there was a significant difference between the target change + touch and distractor change + touch conditions (Bonferroni, $p < .001$). Touching distractors always produced significantly more interference than touching targets.

Are touch latencies higher for distractors than for targets?

During the tracking interval of each trial, there were 2–3 item touches. For each trial, latencies for these 2–3 touches were averaged. There were no inaccurate touches, because the program was designed so that the trial would be terminated if the participant did not touch the item that changed colour within 2 seconds. (In the end, none of the trials had to be terminated;

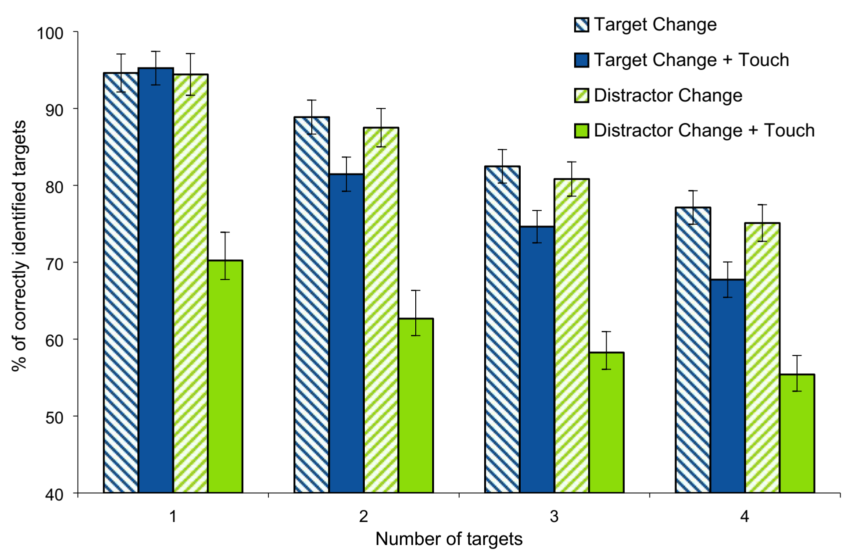

Fig. 4 Experiment 1: Percentage of correctly identified targets in multiple-object tracking (MOT) as a function of task load (single-task: change alone, dual-task: change + touch), item identity (target in MOT, distractor in MOT) and number of targets to track (1–4). Error bars denote 95% CIs

Table 2 Results for the Experiment 1 ANOVA where the percentage of correctly identified targets in multiple-object tracking (MOT) is analyzed as a function of the task load (single task: change alone, dual task: change + touch), item identity (target or distractor in MOT), and number of targets to be tracked in the MOT task (1–4)

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η_p^2
(Intercept)	1.00	63.00		6,219,684.36	88,038.72	4,450.77	.000	.97
Task load	1.00	63.00		552,66.53	10,071.74	345.70	.000	.85
Item identity	1.00	63.00		25,095.07	9,701.80	162.96	.000	.72
Task Load × Item Identity	1.00	63.00		20,853.54	7,764.49	169.20	.000	.72
Number of targets	2.33	147.01	0.78	52,525.27	27,574.11	120.01	.000	.66
Number of Targets × Task Load	2.94	185.02	0.98	434.17	15,317.90	1.79	.153	.03
Number of Targets × Item Identity	2.86	180.44	0.95	1,142.99	13,465.70	5.35	.002	.08
Number of targets × Task Load × Item Identity	2.96	186.24	0.99	2,170.95	15,658.83	8.73	.000	.12

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. Epsilon indicates Greenhouse–Geisser multiplier for degrees of freedom, *p* values and degrees of freedom in the table incorporate this correction. SS_{Num} indicates sum of squares numerator. SS_{Den} indicates sum of squares denominator. η_p^2 indicates partial eta-squared.

the participants always touched the item that changed colour within the 2 seconds.) For each participant, condition, and number of targets, average touch latencies were screened out if they were more than 2.5 standard deviations from that participant's mean for that condition and number of targets. Based on this criterion, 1.59% of the trials were excluded from the analysis.

In order to find out if there was differential interference, we compared average latencies to touch items that changed colour in trials when participants touched targets in MOT as compared with distractors (see Fig. 6). A 2 (identity of the object that changed colour during item motion: target or distractor in MOT) × 4 (numbers of targets: 1–4) factorial ANOVA was performed to determine whether the identity of the object that changed colour had a significant effect on average touch latencies during object motion. The identity of the item did have an effect on touch latencies with latencies larger for distractors than targets, $F(1.00, 55.00) = 19.31$, $p < .001$, $\eta_p^2 = .26$; however, this difference was extremely small ($M_{\text{difference}}$ = 8.9 ms). Interestingly, this mean difference is almost identical to that observed between the touch-target and touch-all conditions in Thornton and Horowitz (2015), a study that also averaged latencies across successive touches during the tracking interval for each trial. The effect of the number of targets was significant, $F(2.89, 159.20) = 3.64$, $p = .015$, $\eta_p^2 = .03$, but the expected interaction between the identity of the item and the number of targets did not emerge, $F(2.84, 156.44) = 1.63$, $p = .187$, $\eta_p^2 = .03$. This was very surprising because we expected that the difference between the target and distractor touch conditions would be especially large when participants were tracking a single target because participants would be obligated to repeatedly touch the same item in the target

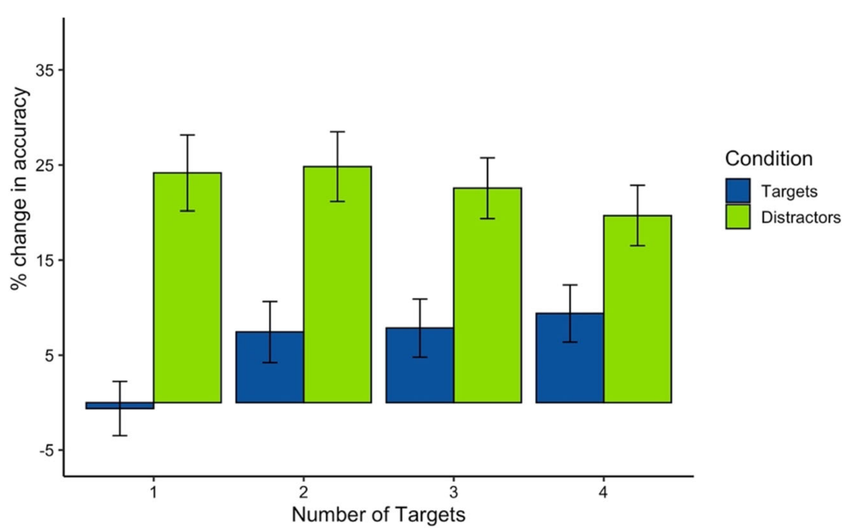

Fig. 5 Interference analysis in Experiment 1, with interference calculated by subtracting the percentage of correctly identified targets in the dual-task condition (change + touch) from the corresponding single-task condition (change alone). Interference (the change in percentage accuracy) is reported as a function of the identity of the item that changed colour (target in MOT, distractor in MOT) and the number of targets to track (1–4). Error bars denote 95% CIs

Table 3 Bonferroni tests as applied to k (tracking capacity) in Experiment 1: Comparisons between change and change + touch for targets and distractors in multiple-object tracking and target and distractor change + touch

Conditions compared	Number of targets			
	1	2	3	4
Target change vs. target change + touch	*n.s.*	***	***	*
Distractor change vs. distractor change + touch	***	***	***	***
Target change + touch vs. distractor change + touch	***	***	***	***

***$p < .001$, **$p < .01$, *$p < .05$

change + touch condition. This prompted us to give additional consideration to the touch latencies.

Although it would not explain results in the one target condition where tracking accuracy was high, when there were more targets, it is possible this minimal difference in latencies could be an artifact of the way the latency data were analyzed. We based analyses on whether the items that changed were assigned to be targets or distractors in MOT—rather than whether the participants considered the items as targets or distractors at the end of the trial, when they reported the target positions. Consequently, if participants were not correct about the locations of 100% of the targets at the end of the trial, then it is possible that the touch latencies in the target change + touch condition might reflect a mixture of items that were truly targets and those that the participant considered to be distractors as indicated by their final report of the target locations. Similarly, if participants were not correct about the locations of 100% of the targets at the end of the trial, then it is possible that the touch latencies in the distractor change + touch condition might reflect a mixture of items that were truly distractors and those that the participant considered to be targets as indicated by their final report of the target locations. As the number of items to be tracked at once increased from 1–4 and the tracking accuracy decreased, there would be a greater and greater probability that the latencies would reflect a mixture of targets and distractors – at least from the participants' perspective. This confusion would tend to reduce differences between the target change + touch and distractor change + touch conditions.

Because of this potential confusion of target and distractor touch latencies, we tried another approach—one that involved excluding latencies for trials where participants did not report the positions of all of the targets correctly at the end of the trial. This strategy was not without drawbacks. The program reported the average touch latency across the 2–3 touches, but it did not record the identity of the touched and reported items. Consequently, every time that there was an error in reporting the locations of one or more targets, we had to drop the average latency for the entire trial because we did not have a record of the individual touch latencies for each item touched. After

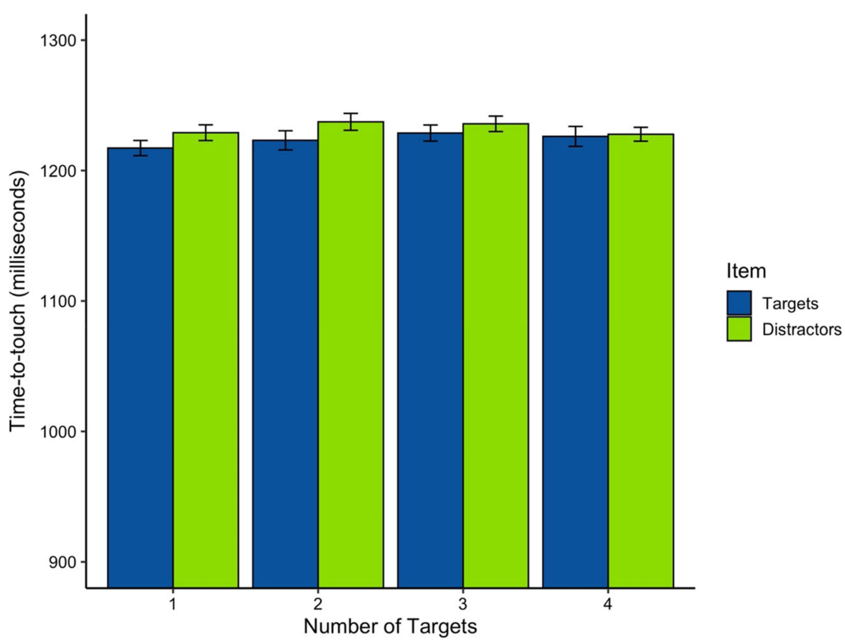

Fig. 6 Experiment 1: Average latencies to touch moving items in multiple-object tracking (MOT) as a function of the item identity (target in MOT, distractor in MOT) and the number of targets to track (1–4). Error bars denote 95% CIs

dropping these trials, there were few participants with enough latency data to analyze in the conditions where MOT was difficult, even if we only required two latencies per cell in the analysis. Although we tried to compensate for this problem by testing a larger sample (we started out with 72 in this study), we were still only left with five participants with enough latency data in each of the cells in the analysis to look at performance for 1–4 targets. With this minimal sample size, none of the effects were significant ($p > .1$), though touch latencies were 12.51 ms faster for targets as compared with distractors. If we restricted our analyses to conditions where the tracking accuracy was still reasonably high (1–2 targets), the difference between the target and distractor touch latencies was still tiny ($M_{\text{difference}} = 10$ ms, $p > .1$).

It is possible that there really is very little difference in latencies to touch items that change colour based on whether they are targets or distractors in MOT. In any dual-task study, there is a danger that participants might put more emphasis on one task than another, prioritizing touch latencies over MOT performance in this case. If that were to happen, then it might be expected that there would be little difference between targets and distractors in touch latency even though there were large differences in tracking performance. However, it is unclear whether these results truly indicate that there is no difference in latencies to touch targets or distractors in MOT, or if it is an artifact of averaging across latencies within a trial. The only way to clarify this uncertainty was to carry out another study using software that kept track of the identities and latencies for each of the items touched and reported.

Discussion

The results of this study provide clear evidence of differential interference in MOT: The identity of the item touched (whether it was a target or distractor in MOT) had an effect on the degree to which touching items that changed colour interfered with MOT. Compared with the corresponding change-alone conditions, touching distractors produced a larger decrement in tracking performance than touching targets (see Fig. 5). This might be expected if touching a distractor caused selection to be diverted from a target to that distractor, causing the target to be "lost" in the final report.

In contrast, when participants touched targets that changed colours it did not interfere as much, and the interference varied with the number of targets to be tracked. In fact, in the extreme case, when there was only a single target to track, there was no significant difference between single-task and dual-task performance in MOT; tracking accuracy in the change-alone condition was as high as in the change + touch condition. This result may be expected if repeatedly touching a given item (the target) made it less likely to be lost during MOT.

However, when it came to touch latencies, the evidence for differential interference was equivocal. We had hypothesized that participants would take markedly longer to touch a distractor that changed colour compared with a target because there would be a preexisting action plan for targets in MOT. Our results revealed a latency difference that was, if anything, miniscule. This tiny difference was especially surprising because this analysis included touch-target latencies when there was only a single target to track. In the touch-target condition when there was a single target, participants would be touching the same item 2–3 times in row, which should have produced a large reduction in touch latencies compared with conditions where participants were touching different items each time (e.g., Bertelson, 1963).

Why was the difference between the touch-target and touch-distractor conditions so small? We followed Thornton and Horowitz (2015) in basing our touch latency measure on the average of multiple touches per trial, a practice that would both ensure a more reliable measure of RT (based on more latencies) and a stronger touch manipulation (with multiple touches per trial). However, averaging in this way may have introduced several sources of variability that may have obscured the latency differences between the target change + touch and distractor change + touch conditions. With 2–3 touches per trial, there an increased probability that one of the items touched was actually a target confused for a distractor or a distractor confused for a target. In addition, there could be repetition effects that occur when participants carry out a series of actions (e.g., Bertelson, 1963). Items could be touched repeatedly, either in immediate succession (which only happened in the target change + touch condition with one target), or after an intervening item. If the same item was touched twice, it might produce priming, which would reduce touch latencies the second time the item was touched, or some variant of inhibition of return (Klein, 2000), which would increase touch latencies the second time the item was touched. Even if participants touched different items every time, it is possible that they would be faster to touch the second item than the first due to some sort of cost to the first item touched within each tracking interval, as if there was some sort of initial "warm up" effect. Consequently, in Experiment 2 we also did an analysis where we compared the latencies for the first and second items touched as well as whether the touched item was a target or distractor in MOT.

Thus, a second study was carried out to help correct for some of the problems in the latency analyses while at the same time allowing us to replicate some of the earlier findings. However, in Experiment 2, our primary goal was to discover if MOT interfered with visually guided touch.

Experiment 2

The initial studies showed that touching items that changed colour interfered with MOT, though the amount of interference varied based on the identity of the item to be touched (target or distractor in MOT). In Experiment 2, we replicated the earlier findings related to MOT performance, but the primary emphasis was on determining whether MOT interfered with visually guided touch as measured by touch latencies. We looked at performance when participants only had to touch items that changed colour (single task: touch alone) as compared with when they had to touch the same items during MOT (dual task: touch + track).

However, carrying out this single-task to dual-task comparison required some initial controls. It is possible the peripheral aspects of the MOT task would affect performance even when participants were *not* actually tracking (i.e., the flashing items at the start of the trial, the need to touch specific items that changed colour and not others during item motion). We wanted to be certain that the only difference between the single-task and dual-task conditions would be that in the latter, participants would be tracking. Therefore, we had to ensure the peripheral conditions in the touch-only trials were exactly the same as those in the corresponding touch + track trials.

Therefore, before comparing single-task and dual-task performance, we did a single-task (touch alone) analysis where we measured touch latencies when there were the same number of flashing items at the start of the trial and the same need to touch specific items during item motion as in the corresponding dual-task trial (touch + track). In this analysis, we investigated the effect of the number of targets (the 1–4 flashing items at the beginning of the trial) and whether the items touched during item motion were targets or distractors (i.e., whether these items were the ones that flashed at the beginning of trial or the ones that did not flash at the beginning of the trial). The inclusion of the one target condition was very useful here because it allowed us to evaluate the effects of touching the same item several times in immediate succession, as occurred in the touch-target condition. We predicted that in single-target trials, latencies would be lower when participants repeatedly touched the same item (the target touch condition) than when they did not (the distractor touch condition). Therefore, we hypothesized an interaction between the number of targets (1–4) and the identity of the item touched (target, distractor) that would disappear once the one target condition was removed from the analysis in the touch-alone trials.

We were also interested in sequence effects: the effects of touching several different items during the course of the 10 second motion phase in the tracking trials. In the previous studies, touch latencies were averaged across 2–3 successive touches per trial. Averaging in this way obscured sequence effects that might vary based on the condition in the analysis. As a result, in Experiment 2 we redesigned the data collection program to enable the comparison of touch latencies between the first and second item touched in the sequence. Another advantage of this modification was that it enabled us to restrict the analysis to latencies for the items that the participants were correct about in MOT without having to drop the latencies for the entire trial if the participants got one of the items wrong (as occurred in the final latency analyses in Experiment 1). That way we could avoid analyzing latencies where participants confused targets with distractors and vice versa. We predicted that the differences between target and distractor touch latencies would emerge when we restricted analyses to items that were only touched once. Moreover, we predicted that participants would be faster to touch the second item in the sequence than the first. This might be expected if part of the first touch latency included an initial cost the first time any item is touched during a tracking trial (cf. Gálvez-García et al., 2014).

Method

Design

As in the previous experiments, participants were required to touch items that changed colour during the item motion phase. We manipulated the number of targets to be tracked and the identity of the item that changed colour (target, distractor), both in single-task and dual-task conditions (touch alone, touch + track). In these analyses, we refer to items as targets and distractors even in the single-task (touch alone) conditions where participants were not tracking. It was necessary to keep targets and distractors separate in the single-task trials to ensure that the only difference between the single-task and dual-task touch conditions was that participants were actually performing the MOT task in the dual-task condition. Otherwise, there would be the possibility that some of the peripheral trappings of the dual-task condition (the initial flashing of some of the items, the requirement to touch a specific subset of items and not others) could contribute to differences in dual-task performance in MOT. Once this analysis was complete, we compared single-task and dual-task touch latencies as a function of the identity of the items to be touched (targets or distractors in MOT) and number of targets in MOT (1–4). The final analyses focused on sequence effects in trials where items were only touched once. Touch latencies were analyzed as a function of the identity of the item touched (target or distractor in MOT), the number of targets in MOT (2–4), and whether the item was the first or second touched in a sequence. Overall, the manipulations used in this study were designed to address the following questions:

(1) Does touching items that change colour interfere with MOT?
(2) Does the flashing of items at the beginning of a trial and the need to touch specific items during item motion have an effect even when participants are not tracking?

(3) Does tracking interfere with touching items that change colour, and is this interference greater when participants touch distractors?
(4) In a sequence of touches, are latencies lower for the second item touched than the first?

Participants

Thirty-seven participants with normal or corrected-to-normal vision were recruited from the University of Guelph psychology participant pool (34 females, $M_{age} = 18.50$, $SE = 0.18$). On average, participants reported 1.96 hours a week playing video games ($SE = 0.54$) and 0.93 hours a week participating in team sports ($SE = 0.40$).

Apparatus and stimuli

The iPad software for the experimental task was modified so that it kept track of the identities of the items touched and reported.

Procedure

Participants were given the same instructions as in Experiment 1. There were two blocks of trials, one single task (touch alone: 32 trials) and the other dual task (touch + track: 64 trials). These two blocks of trials were carried out in a counterbalanced order. Before each block of experimental trials, there were eight practice trials. The study duration was 45 minutes.

Results

Due to program malfunctions, 3 of the 37 participants had incomplete data sets and their data had to be dropped from the analyses. This meant that the remaining sample size was 34, unless otherwise specified. The following section is organized to address the questions set out in the design section.

Does touching items that change colour interfere with MOT?

As in the earlier studies, the percentage of correctly identified targets was analyzed as a function of the identity of the item touched (whether it was a target or distractor in MOT) and the number of target (1–4; see Fig. 7 and Tables 4 and 5). The results replicate those of the earlier studies. Once again, the identity of the item touched had an effect on tracking performance, indicating differential interference, $F(1, 33) = 97.20$, $p < .001$, $\eta_p^2 = .75$. There was also the usual reduction in performance with increases in the number of targets to track, $F(2.48, 81.96) = 30.05$, $p < .001$ $\eta_p^2 = .48$. The interaction between item identity and the number of targets emerged again as well, $F(2.62, 86.51) = 12.90$, $p < .001$, $\eta_p^2 = .28$, with the difference between conditions especially large when there was a single target (Bonferroni, $p < .001$).

Touch latency analyses

For consistency, all participants that were removed from the accuracy analysis were also removed in latency analysis. An additional participant had to be dropped due to technical problems.

Does the flashing of items at the beginning of a trial and the need to touch specific items during item motion have an effect even when participants are not tracking?

Our ultimate goal was to compare latencies to touch items that changed colour as a function of task load (single-task: touch alone, dual-task: touch + track). However, it was important to first ensure that the only difference between the single-task and dual-task conditions would be whether or not the participants were tracking. The dual-task condition would necessarily involve 1–4 items flashing at the beginning of the trial (the target assignment phase of the MOT task) and the need to touch specific items during item motion. We had to ensure that these peripheral aspects of the trial did not have an effect in single-task performance, when all that the participants had to do was touch items that changed colours.

Thus, in the touch-only trials, we analyzed the effect of the number of targets (the 1–4 items that flashed at the beginning of the trial) and the identity of the items that were touched during item motion—that is, whether the touched items were targets (items that flashed at the beginning of the trial) or distractors (items that did not flash at the beginning of the trial). We predicted that there would be an Item Identity × Number of Targets interaction that would disappear once we removed the trials where participants were tracking a single target. This was expected because when tracking one target in the target-touch conditions, participants would have to repeatedly touch the same item, whereas in the distractor-touch condition they would not.

As predicted, there was a significant Item Identity × Number of Targets interaction when there were 1–4 targets: $F(2.58, 82.53) = 3.06$, $p = .040$, $\eta_p^2 = .09$; see Fig. 8). As can be seen from Table 6, neither main effect was significant in this analysis. When there was a single target, latencies were significantly faster when touching targets as compared with distractors, ($M_{difference} = 64.44$ ms, Bonferroni, $p < .001$). These results demonstrated that touch latencies were significantly faster when participants repeatedly touched the same item. Once the one-target condition was removed and analyses were carried out for 2–4 targets, there was no longer a significant interaction (see Table 7).

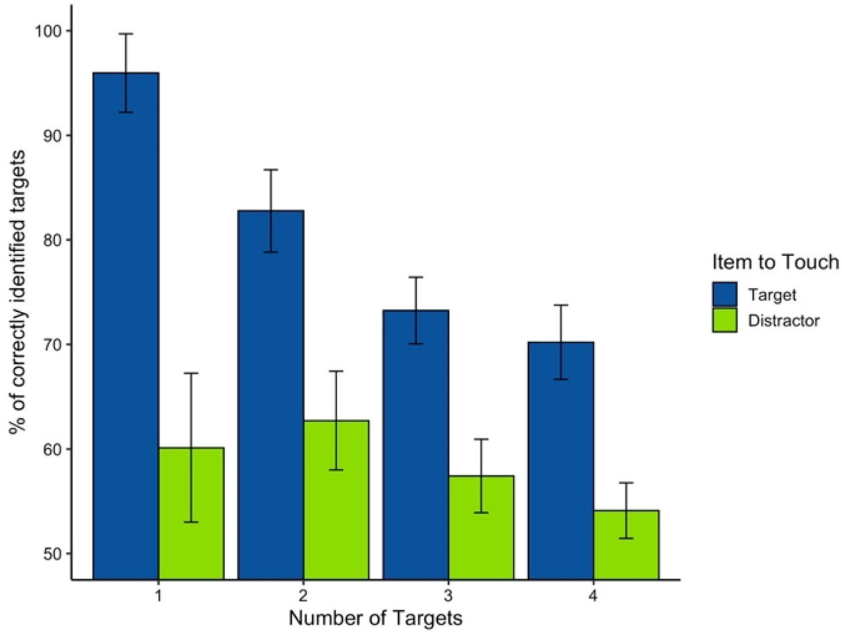

Fig. 7 Experiment 2: Percentage of correctly identified targets in MOT as a function of the item identity (target in MOT, distractor in MOT) and the number of targets to track (1–4). Error bars denote 95% CIs

These results suggest that when there were 2–4 targets, the flashing of 2–4 items at the start of the trial and the need to touch specific items at the end did not produce significant differences in latency. Therefore, there is reason to expect that any differences in touch latencies between the touch-alone and touch + track conditions in future analyses must reflect the demands of tracking while touching items that changed colour.

Does tracking interfere with touching items that change colour, and is this interference greater when participants touch distractors?

The one target conditions were excluded from these analyses because differences between the target and distractor touch conditions emerged in the touch-alone condition, when there was no need to track the items. A 2 × 2 × 3 repeated-measures ANOVA was performed to investigate the effect of task load (single task: touch only, dual-task: touch + track), item identity (target in MOT, distractor in MOT), and the number of items that flashed as targets (2–4) on latencies to touch items that changed colour. Results are presented in Fig. 9 and Table 8. The ANOVA revealed a main effect of task load: $F(1{,}00, 33.00) = 63.22$, $p < .001$, $\eta_p^2 = .66$, providing evidence of *general interference* in that latencies to touch items that changed colour were higher in the dual-task than single-task conditions. There was also a significant effect of item identity, with higher latencies when participants touched distractors as compared with targets, $F(1.00, 33.00) = 11.21$, $p = .002$, $\eta_p^2 = .25$. Most important, the predicted Task Load × Item Identity interaction emerged, which suggests that there was also *differential interference*: $F(1.00, 33.00) = 13.86$, $p = .001$, $\eta_p^2 = .30$. Specifically, in the single-task (touch alone) condition, the difference between target and distractor touch latencies was only 6.38 ms, whereas in the dual-task (touch + track) condition, this difference was 62.47 ms (Bonferroni, touch-only $p > .1$, touch + track $p < .001$).

Interestingly, all main effects and interactions involving the number of targets as a factor were not significant (see Table 8). This finding is important as it suggests that the number of target locations held in working memory for later report has no influence on the average latency to touch items that change colour during the item motion phase of MOT.

Table 4 Experiment 2 tracking capacity (k) when participants were required to track 1–4 targets in two conditions: participants touch targets in MOT that change colour during motion, participants touch distractors in MOT that change colour during motion (MOT: multiple-object tracking)

Number of targets to be tracked	1	2	3	4
Target change + touch	0.96	1.64	2.09	2.51
Distractor change + touch	0.58	1.18	1.44	1.35

In a sequence of touches, are latencies lower for the second item touched than the first?

In the first experiments, the touch latency differences between distractor touch and target touch conditions were minimal. However, in those analyses our data was comprised of touch latencies that were averaged across a sequence of 2–3 touches

Table 5 Results for the Experiment 2 ANOVA where the percentage of correctly identified targets in multiple-object tracking (MOT) is analyzed as a function of the item identity (target or distractor in MOT), and number of targets to be tracked in the MOT task (1–4)

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	F	p	η_p^2
(Intercept)	1.00	33.00		1,316,438.03	24,061.20	1,805.50	.000	.97
Item identity	1.00	33.00		32,777.13	11,128.19	97.20	.000	.75
Number of targets	2.48	81.96	0.83	10,517.66	11,549.69	30.05	.000	.48
Number of Targets × Item Identity	2.62	86.51	0.87	4,558.30	11,663.41	12.90	.000	.28

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. Epsilon indicates Greenhouse–Geisser multiplier for degrees of freedom, p values and degrees of freedom in the table incorporate this correction. SS_{Num} indicates sum of squares numerator. SS_{Den} indicates sum of squares denominator. η_p^2 indicates partial eta-squared

per trial (each trial involved a tracking interval of 10 seconds). That means that within any given trial there could be latencies from items that were touched just once and latencies from items that were touched several times, latencies for targets confused for distractors (or vice versa), and latencies for items that were truly targets or distractors in MOT. In the present set of comparisons, we restricted our analysis to latencies for items that had only been touched once. Consequently, data from the one-target condition were excluded. We also screened out any touch latencies where the participant was not correct about whether the item was a target or distractor in the final report. Latencies were analyzed as a function of the item identity (target or distractor in MOT), number of targets to be tracked (2–4), and touch number (whether the item was the first or second to be touched in the sequence of touches in a given tracking interval). Four participants had such poor performance that they did not have latencies for both the first and second touch in each condition, and consequently their data had to be dropped from these analyses.

As predicted, there was evidence of *differential interference*; a main effect of item identity emerged, $F(1.00, 29.00) = 18.27$, $p < .001$, $\eta_p^2 = .39$. Results are presented in Fig. 10 and Table 9. Latencies to touch items that changed colour were on average 62.25-ms higher when the item was a distractor as compared with a target in MOT. Furthermore, as hypothesized, in a sequence of touches, latencies were higher for the first item touched than the second ($M_{\text{difference}} = 82.72$ ms), $F(1.00, 29.00) = 20.61$, $p < .001$, $\eta_p^2 = .42$. However, there was also an unexpected three-way interaction (Item Identity × Number of Targets × Touch Number), $F(1.98, 57.32) = 5.05$, $p = .010$, $\eta_p^2 = .15$, which appears to be driven primarily by the two-target condition. At this point, the

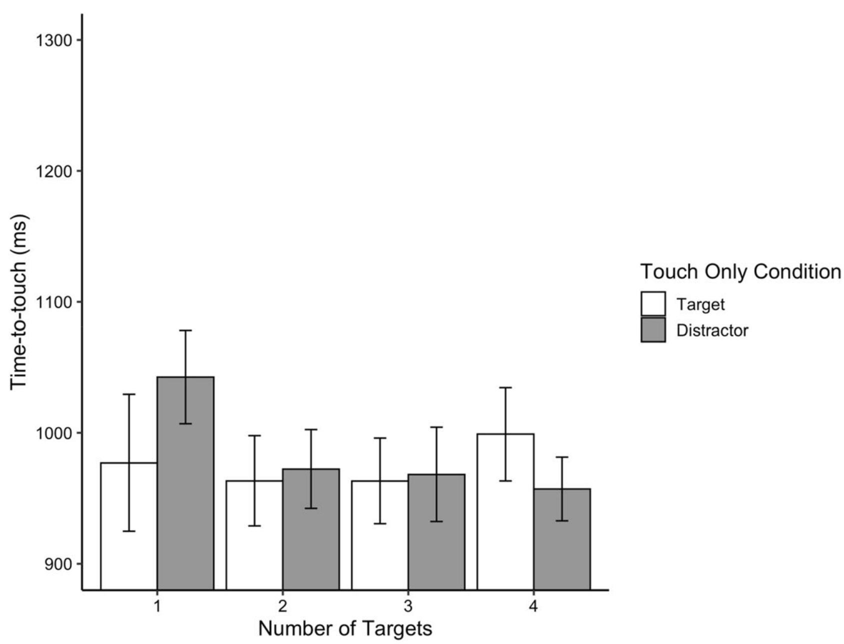

Fig. 8 Experiment 2: Average time to touch the items that changed colour (in milliseconds) during the touch-only trials (single-task) as a function of the identity of the changing item (target, distractor) and the number of items that originally flashed (1–4). Note that for the touch–only conditions, the participants are not multiple-object tracking. The targets are the items that flash at the beginning of the trial before item motion starts. The distractors are the items that do not flash at the beginning of the trial before item motion starts. Error bars denote 95% CIs

Table 6 Results for the Experiment 2 ANOVA analyzing the average time to touch the items that changed colour (in milliseconds) during the touch-only trials (single task) as a function of the identity of the changing item (target, distractor) and the number of items that originally flashed (1–4)

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	F	p	η_p^2
(Intercept)	1.00	32.00		25,376,7591.35	2,310,531.06	3,514.59	.000	.99
Item identity	1.00	32.00		5,876.94	285,698.52	0.66	.423	.02
Number of targets	2.34	75.00	0.78	82,070.95	1,014,291.61	2.59	.073	.07
Number of Targets × Item Identity	2.58	82.53	0.86	95,315.74	995,763.69	3.06	.040	.09

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. Epsilon indicates Greenhouse–Geisser multiplier for degrees of freedom, p values and degrees of freedom in the table incorporate this correction. SS_{Num} indicates sum of squares numerator. SS_{Den} indicates sum of squares denominator. η_p^2 indicates partial eta-squared

explanation for this anomaly at two targets is unclear. As can be seen from Table 9, none of the other effects were significant.

Discussion

Overall, this study showed interference between MOT and visually guided touch (touching items that changed colour). Not only was performance worse when the two tasks were carried out at the same time (general interference), but this reduction in performance was especially pronounced when participants touched items that were distractors in MOT rather than targets (differential interference). Differential interference was evident in terms of MOT accuracy; this shows that touch interferes with MOT. However, it was also evident in terms of response latencies to touch items that change colour; this shows that MOT interferes with visually guided touch. Unlike the earlier studies, in Experiment 2, there was a marked difference in touch latencies for targets as compared with distractors in MOT. This may be explained by refinements in the data collection program in Experiment 2. However, this difference may have also occurred because touching the items that changed colour was less of a novelty in Experiment 2. In the first studies, participants only had to touch items that changed colour in 2 of 5 conditions. In contrast, in Experiment 2, participants had to touch items that changed colour in every trial.

There were several other incidental findings in Experiment 2. First, the results demonstrated that even when participants were not performing the MOT task, latencies were lower when touching a single item repeatedly as compared with touching different items. Given that the items were always moving and occupied different positions each time they were touched, this result provides evidence of an object-based type of priming. Second, when participants were touching two different items over a 10-second tracking interval, latencies for touching the first item were significantly greater than for the second, suggesting there may be some sort of initial cost for touching the first item in a series. However, this sequence effect did not negate the touch latency difference between targets and distractors.

General discussion

These studies were designed to investigate the relationship between MOT and visually guided touch by making use of the dual-task procedure. Participants tracked moving targets among distractors while at the same time touching any items that changed colour during the tracking interval. Overall, these studies showed that although the need to touch items that changed colour while carrying out the MOT task did not render either task impossible, there was interference between tasks. Single-task performance was almost always better than

Table 7 Results for the Experiment 2 ANOVA analyzing the average time to touch the items that changed colour (in milliseconds) during the touch-only trials (single task) as a function of the identity of the changing item (target, distractor) and the number of items that originally flashed (2–4)

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	F	p	η_p^2
(Intercept)	1.00	32.00		186,532,447.76	1,513,582.62	3,943.65	.000	.99
Item identity	1.00	32.00		4,220.07	317,574.71	0.43	.519	.01
Number of targets	1.70	54.46	0.85	5,707.58	464,912.87	0.39	.644	.01
Number of Targets × Item Identity	1.97	63.15	0.99	26,301.70	483,894.40	1.74	.184	.05

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. Epsilon indicates Greenhouse–Geisser multiplier for degrees of freedom, p values and degrees of freedom in the table incorporate this correction. SS_{Num} indicates sum of squares numerator. SS_{Den} indicates sum of squares denominator. η_p^2 indicates partial eta-squared

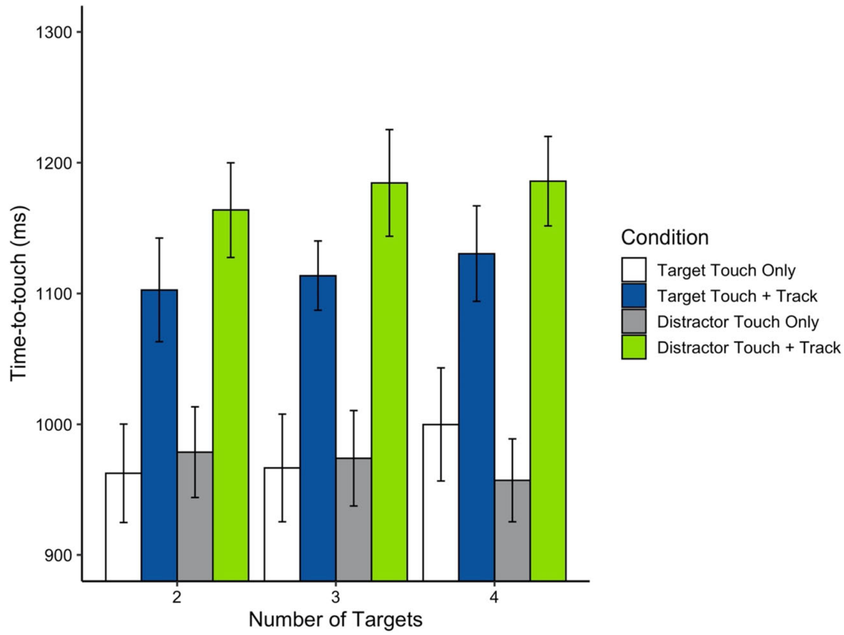

Fig. 9 Experiment 2: Average time to touch the items that changed colour (in milliseconds) as a function of the task load (single-task: touch-only, dual-task: touch + track), the item identity (target, distractor), and the number of items that originally flashed (2–4). Note that for the touch-only conditions, the participants are not multiple-object tracking. The targets are the items that flash at the beginning of the trial before item motion starts. The distractors are the items that do not flash at the beginning of the trial before item motion starts. In the dual-task (touch + track) conditions, participants have to track the targets as well as touch the items that change colour. Error bars denote 95% CIs

dual-task performance. As might be expected from previous studies (e.g., Allen et al., 2006; Kunar et al., 2008; Thornton & Horowitz, 2015; Trick et al., 2006), there was evidence of *general interference*—that is, an overall difference between single-task and dual-task performance, with dual-task performance being worse. General interference was shown in two ways. First, MOT performance was almost always worse when participants had to touch items that changed colour during the tracking interval. This difference could not be attributed to the effects of colour change per se because colour change had no effect on MOT when participants did not have to touch items that changed colour. Second, latencies to touch items that changed colour were higher when participants also had to carry out an MOT task at the same time.

General interference of this type might be attributed to the working memory demands of coordinating two tasks at the same time. If these two tasks were thought to involve action plans, then in the dual-task condition participants could be maintaining multiple action plans at once, one immediate (touch any item than changes colour) and one more remote (touch targets in MOT once the items stop moving). When several action plans are carried out in a sequence, each must be

Table 8 Results for the Experiment 2 ANOVA analyzing the average time to touch the items that changed colour (in milliseconds) as a function of the task load (single task: touch-only, dual-task: touch + track), the item identity (target, distractor), and the number of items that originally flashed (2–4)

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η_p^2
(Intercept)	1.00	33.00		458,388,291.65	3991617.82	3789.64	.000	.99
Task load	1.00	33.00		3,077,542.81	1,606,438.52	63.22	.000	.66
Item identity	1.00	33.00		80,247.85	236,194.64	11.21	.002	.25
Task load × Item Identity	1.00	33.00		120,889.02	287,782.53	13.86	.001	.30
Number of targets	1.72	56.79	0.86	18,331.72	497,899.60	1.21	.300	.04
Number of Targets × Task Load	1.98	65.43	0.99	6,262.98	436,176.29	0.47	.623	.01
Number of Targets × Item Identity	1.97	65.17	0.99	24,051.58	608,692.61	1.30	.278	.04
Number of Targets × Task Load × Item Identity	1.93	63.67	0.96	12,374.39	374,156.53	1.09	.340	.03

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. Epsilon indicates Greenhouse–Geisser multiplier for degrees of freedom, *p* values and degrees of freedom in the table incorporate this correction. SS_{Num} indicates sum of squares numerator. SS_{Den} indicates sum of squares denominator. η_p^2 indicates generalized eta-squared.

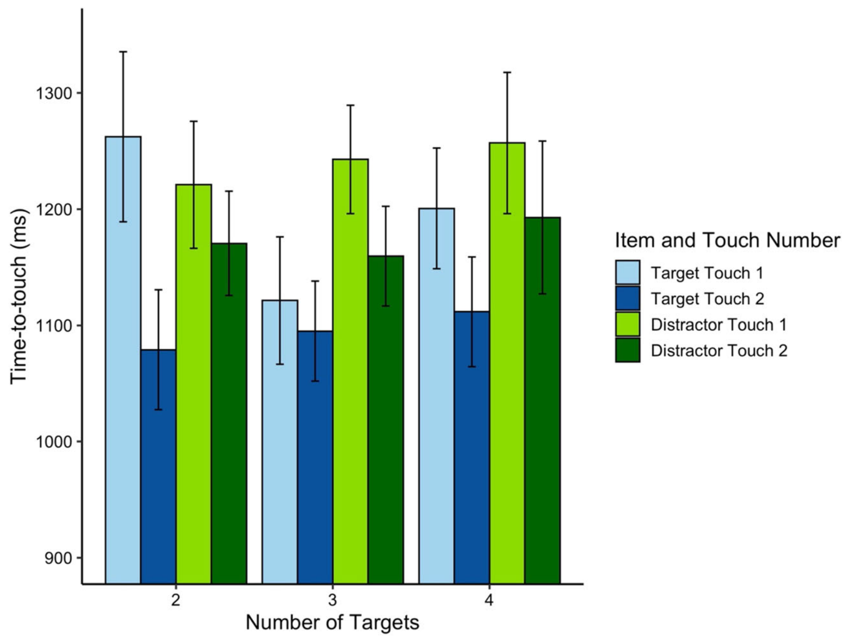

Fig. 10 Experiment 2: Average time to touch the item that changed colour (in milliseconds) as a function of the item identity (target in MOT, distractor in MOT), whether the item was first or second item touched in the series of touches in the trial, and the number of targets to track (2–4). Please note that all response times reflect cases where participants touched the item in question and were correct about that item in the final report phase of the MOT task. Error bars denote 95% CIs

stored in working memory (e.g., Fournier et al., 2014), though in this case, the most critical aspect of these plans would be the target locations. If working memory demands were directly related to touch latencies, that would mean there would be reason to expect the latencies to touch items would increase with the number of targets to be tracked at once. However, there was no evidence of this in our data. In the present studies, general interference between visually guided touch and tracking may also reflect the effects of extraneous eye movements. It is possible that when participants have to touch items as they move, they may make more eye movements than they normally do during tracking. These eye movements may impede MOT.

However, in these studies, we were primarily interested in whether MOT and visually guided touch involve the same mechanism. In contrast, general interference may occur between tasks that are not carried out by the same mechanism, though they may require the same limited-capacity resources (e.g., working memory, general attention). Consider MOT and a cell phone conversation, for example (Kunar et al., 2008). In order to demonstrate that the mechanisms used in MOT were actually part of visually guided touch, we had to

Table 9 Results for the Experiment 2 ANOVA analyzing the average time to touch the item that changed colour (in milliseconds) as a function of the item identity (target in MOT, distractor in MOT), whether the item was first or second item touched in the series of touches in the trial, and the number of targets to track (2–4)

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η_p^2
(Intercept)	1.00	29.00		498,277,974.99	6,509,472.68	2,219.85	.000	.99
Item identity	1.00	29.00		339,977.11	569,666.02	17.31	.000	.39
Touch number	1.00	29.00		604,179.72	865,891.19	20.23	.000	.42
Item Identity × Touch Number	1.00	29.00		22,940.37	750,806.44	0.89	.354	.03
Number of targets	1.80	52.11	0.90	87,927.73	1,399,057.78	1.82	.175	.06
Targets × Item Identity	1.64	47.67	0.82	76,281.83	1,011,855.27	2.19	.132	.07
Number of Targets × Touch Number	1.89	54.90	0.95	54,751.66	1,281,314.05	1.24	.296	.04
Number of Targets × Item Identity × Touch Number	1.97	57.26	0.99	128,977.57	767,681.01	4.87	.011	.15

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. Epsilon indicates Greenhouse–Geisser multiplier for degrees of freedom, *p* values and degrees of freedom in the table incorporate this correction. SS_{Num} indicates sum of squares numerator. SS_{Den} indicates sum of squares denominator. η_p^2 indicates generalized eta-squared.

find evidence of *differential interference*—that is, differences in the amount of interference produced by touching items that changed colour based on the role that the items played in MOT: whether the items were targets as opposed to distractors in tracking. In these studies, we found evidence of differential interference in terms of MOT performance and touch latencies. When participants touched items that changed colour during MOT, performance was significantly worse when those items were distractors rather than targets. This might be expected if touching distractors interfered because touching distractors caused those items to be selected and therefore tracked at the expense of the targets that were to be reported in MOT.

Thus, although general interference might be due to competition for a common limited resource such as general working memory or whatever is necessary to "pay attention," differential interference (the differences in the effect of touching items that changed colour depending on whether those items were targets or distractors), would be more likely to reflect processes specific to selecting and individuating targets. There is considerable controversy about how individuation is accomplished, whether it is by mental reference tokens that keep track of the locations of individual items (FINSTs: Pylyshyn, 2001) or by some sort of multifocal attention (e.g., Cavanagh & Alvarez, 2005), but in these studies it is clear that touching items seems to have an effect on item selection. This may be because participants confuse touched items with targets in MOT, resulting in reductions in accuracy when participants touched distractors. In contrast, when participants touched targets, this might improve tracking performance by reinstating targets that were "lost" during item motion or reinforcing selection in items not yet lost, increasing the amount of attentional resources devoted to those items (e.g., Alvarez & Franconeri, 2007; Thornton et al., 2014).

In fact, we have some preliminary evidence from Experiment 2 that is relevant to both of these predictions. Unfortunately, the study was not optimally designed to address the question of whether touched items were more likely to be reported because there were 2–3 item touches per trial. This meant there were up to three different items touched in any given trial and therefore, the only data that we could analyze to answer this question came from trials there were four targets to track. However, when there were four targets to track, in the distractor touch condition, distractors were 5% more likely to be *incorrectly* reported as targets in MOT if they were touched rather than untouched during tracking. Conversely, in the target-touch condition, targets were 10% more likely to be *correctly* reported as targets in MOT if they were touched rather than untouched during tracking. While these results provide some preliminary evidence that touched items are more likely to be reported as targets, this issue would be better investigated in a study where there was only a single item touch per trial.

There was also evidence of differential interference as can be seen in the latencies to touch items that changed colour, with the results most pronounced in Experiment 2, when participants touched items that changed colour during every trial. We found that although repeatedly touching the same item can yield latency advantages (as can be seen in the target-touch condition when there was a single target even without MOT), this difference was even apparent when we restricted the analyses to the first time each item was touched. This differential interference in touch latencies might be expected if the targets in MOT had an initial advantage; in the touch-target condition, the targets had already been selected at the beginning of MOT trial during target assignment phase. For the targets, the first stages of the action plan would be already underway, and this may reduce the latency to touch those specific items when they change colour during item motion. In contrast, touching items that changed colour took longer when the items were distractors because the distractors were not yet selected/individuated and thus there was no developing action plan for distractors.

Moreover, this latency difference between target and distractor touch trials maintained over a series of touches during the item motion phase of the tracking trial. We compared latencies for the first as opposed to the second item touched. Although we found a touch latency advantage for the second item, this difference did not interact with the identity of the item that was touched (whether it was a target or distractor in MOT). When participants simply had to touch items that changed colour, the latency advantage for touching items that were targets in MOT did not disappear after the first item touched.

Thus, overall, there was evidence of both general and differential interference between tasks. There were also interesting findings related to the effects of different numbers of targets. The one target condition was especially informative. In MOT, when the number of targets is manipulated, performance is always best when there is only one target (e.g., Trick et al., 2006), but in this study, when participants had to touch a single target as it moved, touch no longer interfered with MOT (see Fig. 5). In fact, dual-task performance was slightly better than single-task in the target change + touch condition, though performance was close to ceiling and the difference was not statistically significant. Although the items were always moving, and occupied different positions at every time, there were benefits to touching the same item repeatedly. We found that even without the tracking task, touch latencies were lower when participants repeatedly touched the same item (see Fig. 8) which suggests that demands of touching a *specific* item decline with repeated touches and consequently, touching that item interferes less with tracking. When participants only have to track a single target, touching the target may even facilitate tracking because it may help participants concentrate and stay on task. Tracking a single item is so easy that it may be difficult for participants to stay focused on the task.

This investigation leaves many unanswered questions, though. First, the role of eye movements in interference between MOT and visually guided touch should be investigated. Moreover, in these studies, both tasks required participants to touch items with the index finger of their right hand. Fournier et al. (2014) showed that when there are several action plans at once, these action plans can interfere with each other to the extent that they share common elements. It is possible that there might be less interference if the tasks did not both involve the index finger of the dominant hand (e.g., see Gálvez-García et al., 2014).

Consequently, in future investigations it would be useful to explore whether visually guided touch interfered as much with tracking in tracking tasks where participants reported the identity of targets using a different modality than touch. For example, during the report phase of each tracking trial, a letter could be posted beside each item (e.g., A–J on a 10-item display), and participants could report the targets by saying the letters associated with those items. In fact, there may even be different patterns of performance in a MOT task where index fingers are used to make a response, but the required response did not involve pointing at the actual location of the target. For example, in the probe-one variant of the MOT paradigm (Meyerhoff et al., 2017), one of the items flashes at the end of the item movement phase of the tracking trial. In this variant, participants respond by pressing one button if the item is a target and another if the item is a distractor. Thus, the next stage in this research is to find out whether the link between MOT and visually guided touch is intrinsic to the perceptual requirements of MOT or merely an artifact of the way that participants report the identity of the targets at the end of the tracking trial.

Furthermore, in this study we restricted our investigation to items that played a role in MOT (targets or distractors). A baseline condition that measured touch latencies for colour changes that occur in items that are neither targets nor distractors in MOT would be informative. In a probe detection study, Pylyshyn (2006) found evidence for inhibition of distractors in MOT (see also Bettencourt & Somers, 2009). It is possible the effects observed in these studies do not really represent an advantage for touching targets so much as a disadvantage for touching distractors. The inclusion of a baseline condition would be useful in resolving this issue.

In conclusion, although the findings from these studies should be replicated using different tracking paradigms and eye-movement analysis, in showing differential interference between MOT and visually guided touch, these studies provide preliminary support for Pylyshyn's (2001) contention that there is a link between the mechanisms used in MOT and visually guided touch. The nature of this link has yet to be explored.

Acknowledgements This project was supported by a grant to the second author from the Natural Sciences and Engineering Research Council of Canada (Discovery Grant: 400713). This study represents an equal collaboration between Mallory Terry and Lana Trick (names are in alphabetical order). Some of the studies presented here were presented at the annual meeting of the Canadian Society for Brain, Behaviour, and Cognitive Science and the Psychonomic Society. We would like to thank Ian Thornton for his advice and help in designing the software used in the study and his comments on earlier drafts of the paper. Correspondence concerning this document should be addressed to Lana Trick, Dept. of Psychology, University of Guelph, Guelph, Ontario, Canada N1G 2W1. E-mail: ltrick@uoguelph.ca

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Open practices statement None of the studies in the document were preregistered. The results of the supplementary experiment and the data from all experiments are available on the Scholars Portal Dataverse page associated with this paper (https://doi.org/10.5683/SP2/WE9TOY).