american physiological society

JNP JOURNAL OF NEUROPHYSIOLOGY

J Neurophysiol 129: 115–130, 2023.
First published December 7, 2022; doi:10.1152/jn.00305.2022

RESEARCH ARTICLE

Control of Movement

The influence of movement-related costs when searching to act and acting to search

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Abstract

Real-world search behavior often involves limb movements, either during search or after search. Here we investigated whether movement-related costs influence search behavior in two kinds of search tasks. In our visual search tasks, participants made saccades to find a target object among distractors and then moved a cursor, controlled by the handle of a robotic manipulandum, to the target. In our manual search tasks, participants moved the cursor to perform the search, placing it onto objects to reveal their identity as either a target or a distractor. In all tasks, there were multiple targets. Across experiments, we manipulated either the effort or time costs associated with movement such that these costs varied across the search space. We varied effort by applying different resistive forces to the handle, and we varied time costs by altering the speed of the cursor. Our analysis of cursor and eye movements during manual and visual search, respectively, showed that effort influenced manual search but did not influence visual search. In contrast, time costs influenced both visual and manual search. Our results demonstrate that, in addition to perceptual and cognitive factors, movement-related costs can also influence search behavior.

NEW & NOTEWORTHY Numerous studies have investigated the perceptual and cognitive factors that influence decision making about where to look, or move, in search tasks. However, little is known about how search is influenced by movement-related costs associated with acting on an object once it has been visually located or acting during manual search. In this article, we show that movement time costs can bias visual and manual search and that movement effort costs bias manual search.

decision making; manual search; movement costs; reaching; visual search

INTRODUCTION

Visual search behavior in humans has been studied extensively, with evidence suggesting that search is driven by both bottom-up (i.e., stimulus driven) and top-down (i.e., goal oriented) influences on attention (1–6). Most studies of search behavior have used visual search tasks that involve locating a target item and producing a response (e.g., a button press) once it is located. However, real-world search behavior often involves significant movement, whether moving within and acting on the environment to perform the search, "acting to search," or acting on a target object once it has been visually located, "searching to act" (for reviews see Refs. 7–9). The aim of our study was to test the hypothesis that movement-related costs, including effort and time costs, can influence search behavior both when acting to search and when searching to act.

In experimental visual search tasks, there is often a single target located among distractors. However, in many real-world search tasks there are multiple targets, as when visually searching for one of a pair of oven mitts or one of several cutting knives while cooking. In this scenario, movement-related costs involved in retrieving the target object can be reduced by first visually searching nearby locations, requiring less time and effort to move to, and only then visually searching more distant locations. (Note that this account makes the reasonable assumption that search is terminated when a target object is found; it would be neither time

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Submitted 20 July 2022 / Revised 29 November 2022 / Accepted 30 November 2022

efficient nor sensible to first search distant locations for a target object and then, if a target is located, ignore it and continue searching nearby locations.) In contrast to searching to act, when acting to search it is advantageous to search nearby locations (or more generally easy-to-get-to locations) even when there is a single target object. For example, when looking for the single garlic press in someone else's kitchen, movement-related costs can be reduced, on average, by first opening nearby drawers. However, the cost advantage of searching easy-to-get-to locations when acting to search increases when there are multiple target objects (since the probability of having to search in hard-to-get-to locations decreases).

To test our hypothesis, we designed a series of experiments in which participants searched a display containing multiple target objects, located among distractor objects, and incurred movement-related costs when either moving a cursor to a target object after visually locating it (visual search) or moving a cursor to objects in the scene to reveal whether a given object was a target or a distractor (manual search). In both cases, search terminated when the first target object was found. To our knowledge, previous research has not directly examined whether visual or manual search can be influenced by movement-related costs associated with reaching toward or locating a target object. However, costs associated with movement have been shown to influence decision making in sensorimotor and perceptual tasks as well as the extent to which memory resources are exploited in search tasks.

Movement costs, such as energy expenditure, are an integral component of most models of motor control and can influence decisions about how to move to achieve a movement goal, including how to respond to feedback during the movement (10–13). Movement effort can also influence action selection. For example, in a task in which participants could freely choose between two possible reach targets, participants preferred movements to the target associated with less biomechanical effort (14–16). Similarly, when walking, people select footholds that minimize energetic costs through the maintenance of a stable gait (17, 18). Movement costs associated with responding are also capable of biasing decision making in perceptual judgment tasks (19, 20). Hagura et al. (19) asked participants to report whether they saw dots in a display moving coherently either to the left or to the right by moving either the left or right hand, respectively. Participants held a handle in each hand, which applied a resistive load during hand movement. When the resistive load incurred when moving one of the hands was increased relative to the other hand, perceptual judgments became biased toward the direction associated with the hand that was easier to move. In a similar experiment, participants reported the direction of dot motion by reaching to a target located on the left or right (21). After initiating the reach, participants sometimes changed their mind, based on visual evidence obtained after the initial decision to move, and reversed their reach direction. It was found that participants were less likely to change their mind when the two targets were far apart, such that greater effort was required to correct the movement. Together, this work suggests that, when relaying a decision via arm movements, costs incurred at the output level of the motor system can seemingly influence processes occurring at the level of the visual-perceptual system.

A handful of studies have shown that people are more likely to use memory to guide search, and thereby reduce movement-related costs, when search involves more effortful movement (22–28). Solman and Kingstone (28) examined a search task in which participants viewed items with different letters on them and where the target letter was varied from trial to trial. The locations of the items were either randomized on each trial or repeated across trials. In addition, the size of the display was varied such that search either required both eye and head movements or only eye movements. The authors found that the reduction in search time between randomized and repeated displays was greater when search required both eye and head movements. This suggests that when search required head movements, participants exploited memory of the items to a greater extent, thereby reducing the number of movements required to locate the target (28). Recent studies examining search in virtual environments, in which participants walk around, have also reported that participants rely more strongly on memory than in standard laboratory search tasks (24–26). Ballard and colleagues (22) also showed that costs associated with gaze shifts can influence the contribution of memory in a task in which participants had to arrange a set of blocks to match a visible model showing the desired arrangement. They found that participants fixated the model less frequently when gaze shifts, between the model and the set of blocks, required more costly head movement in comparison to when they only required less costly eye movement. Together, these studies demonstrate how increased effort leads to an increased influence of memory on search performance and decision making.

Across four experiments, we examined movement-related costs, including effort and time costs, in both visual and manual search. To assess effort costs, we applied forces to the hand through the handle of a robot manipulandum that the participant moved to control the position of the cursor. To assess time costs, we had participants move the cursor with a joystick and manipulated the speed of the cursor. These costs were always on a spatial gradient, such that the cost of moving depended on the spatial location of the cursor in the search space. Because multiple target objects were presented in each trial and randomly distributed in the display, participants could lower movement-related costs, across trials, by first searching in low-cost locations. If the costs of movement are factored into search decisions, we would expect to see a shift in search behavior, with search being directed toward locations that reduce movement effort or duration.

In *experiment 1* we tested whether movement effort influences visual search, using a "search-and-then-reach" task in which participants were asked to visually search for a target object among distractors and then reach for the target using a cursor controlled by the handle of a robotic manipulandum. Participants were required to visually locate one of two targets and then move a cursor from the center of the display onto the target object. The target and distractor objects were designed such that identifying the target object required foveal vision. Therefore, we could use eye movements to determine where a participant was searching for the target. We manipulated the effort associated with reaching to the target by applying a large resistive, viscous (i.e., velocity dependent) force to the handle when it moved on either the left or right side of the search space (counterbalanced across participants). We predicted that participants would avoid searching the side of space associated with greater movement costs (i.e., greater viscosity).

The aim of *experiment 2* was to examine whether, and if so how, effort costs that are incurred during search influence search behavior. In this experiment, participants performed an "act-to-search" task in which hand movements were required to perform the search. Participants moved the handle of a robotic manipulandum to move the cursor to objects in a display in order to reveal the identity of the object (target or distractor). If the revealed object was a target, the trial ended; otherwise participants had to continue their search. We applied an elastic force to the handle that was proportional to its distance from the start position such that greater effort was required to place the cursor on objects located farther from the start. Across blocks of trials, participants searched for a target object with the elastic force turned either on or off. We predicted that when the elastic force was on, participants would visit, on average, objects closer to the start location in comparison to when the elastic force was off.

In *experiments 3* and *4* we tested whether movement time costs influence manual and visual search, respectively. The manual search task involved moving a cursor to an object to reveal its identity (target or distractor), and the visual search task required foveating an object to determine its identity. In the manual search task performed in *experiment 3*, cursor movement was controlled by a joystick. We manipulated the time required to move in different regions of the search space by modifying the speed of the cursor based on its radial angle from the start position, with the cursor moving faster when it was located on either the left or right side of the search space (counterbalanced across blocks). We predicted that participants would more often visit objects (to determine whether the object is a target) on the side of space associated with faster cursor speeds. In *experiment 4*, participants performed a block of trials in the manual search task with the cursor moving faster on one side of the search space and then completed a block of visual search trials with the same cursor speed mapping. Participants then performed two additional blocks of the manual and visual search tasks with the cursor moving faster on the other side of the search space. We included these manual search trials to ensure that participants understood how time costs varied across the search space. We predicted that in visual search trials search (as measured by gaze) would be biased to the side with the faster cursor movements.

METHODS

General Methods

A total of 51 participants (27 women) between the ages of 18 and 24 yr completed the experiment. These included 11, 16, 12, and 12 participants in *experiments 1*, *2*, *3*, and *4*, respectively. All participants were right handed and had normal vision or corrected-to-normal vision while wearing contacts. Participants were compensated $15 or 1.0 course credit for their participation. Participants provided written informed consent, and after the conclusion of the experiment they were debriefed. The experiment was approved by the Queen's General Research Ethics Board and complied with the Declaration of Helsinki.

In all experiments, seated participants used their dominant hand to grasp the handle of a planar robotic manipulandum (Fig. 1*A*; Kinarm End-Point; Kinarm, Kingston, ON, Canada) and viewed visual stimuli, including the target objects, distractor objects, and a cursor (filled white circle, radius 3 mm) controlled by handle movement, on a vertical monitor positioned directly in front of them. The position and velocity of the handle and forces applied by the handle to the hand were recorded at 1,000 Hz. In *experiments 1* and *4*, gaze data were collected at a rate of 500 Hz with an infrared eye tracker (EyeLink 1000; SR Research, Ottawa, ON, Canada) mounted just below the display monitor. A chin rest (not shown in Fig. 1*A*) was used to limit head motion during the experiment.

Gaze data were collected when examining visual search tasks in which a participant first located a target object via saccadic eye movements and then reached to the target. After elimination of blinks, the raw gaze position signals (x and y) were smoothed with a second-order, zero-phase lag Butterworth filter with a cutoff frequency of 50 Hz. We then extracted the fixation locations for each trial from the time the objects were presented until reach onset (i.e., the time at which hand speed exceeded 5 cm/s), excluding the first fixation location centered on the fixation cross. To find these fixation locations, we first identified the onset and offset of all saccades by finding when gaze speed (the magnitude of gaze velocity) increased above, and dropped below, 100 cm/s (corresponding to 141°/s with gaze at the center of the search space). For all fixation periods between successive saccades, we computed the average gaze position and then assigned each fixation to one of the search objects. Specifically, we assigned each fixation to the closest object, provided it was no more than 2 cm in distance from the center of that object. Less than 1% of all fixations could not be assigned to an object. Note that when successive fixations were occasionally located at a single search object (which occurred when participants occasionally made small saccades at a given object), we only considered the first fixation.

Experiment 1: Effort Costs in Visual Search

Materials.

The position of the cursor on the monitor was linked to the position of the handle in a horizontal plane. The mapping between handle and cursor movement was the same as a standard computer mouse, such that forward and backward movements of the handle moved the cursor up and down and right and left handle movements moved the cursor right and left. When the cursor was in the center of the screen, the handle was located ~20 cm in front of the participant's chest and in the midsagittal plane. There was a 1:1 correspondence between the distance moved by the handle in the horizontal plane and the distance moved by the cursor on the screen. Figure 1*B* shows the visual stimuli presented to a participant, as well as the gaze (dashed black trace) and cursor (solid black trace) paths produced by the participant, in a single

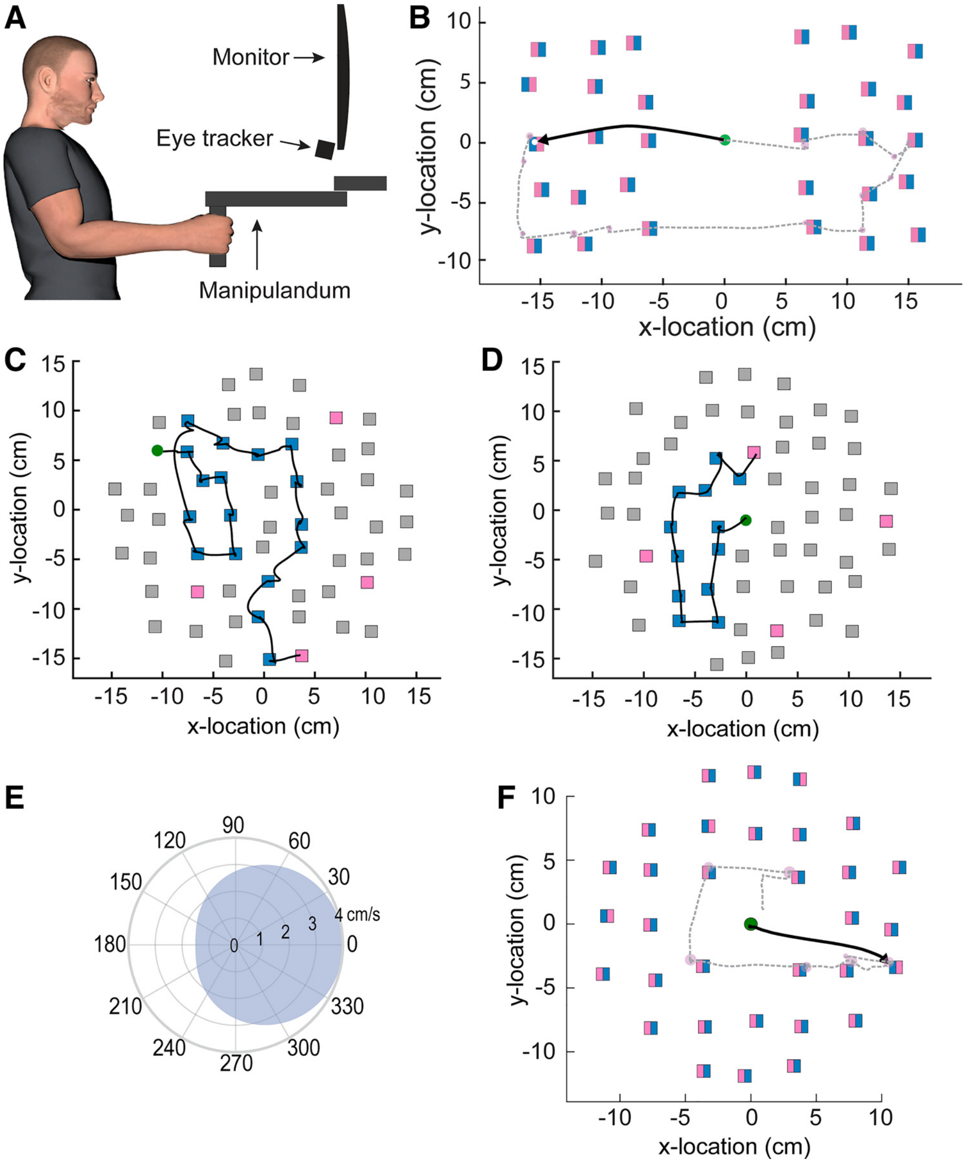

Figure 1. *A*: experiment setup to record hand and eye movement during search. *B*: example search display in *experiment 1* containing 2 target objects (right side pink) and 28 distractor objects (left side pink). Dashed and solid traces show gaze and cursor paths, respectively, in a single trial. Gaze and the cursor were at the start position (green circle) at the start of the trial. *C*: example search display in *experiment 2*. In each trial, 60 objects were presented in a circular grid with the object position within each grid cell randomly jittered. The 60 objects included 4 target objects and 56 distractors that turn pink or blue when visited with the cursor. The black line shows a cursor path for a single trial. The path started at the start position (green), which varied from trial to trial, and ended at the first target found. *D*: example search display in *experiment 3*. The search objects were arranged as in *experiment 2* (*C*) except that start position (green) was always in the center. The black line shows a cursor path for a single trial. *E*: polar plot indicating the relationship between cursor angle and the maximum speed of the cursor (perimeter of the blue shaded area) in the slow-left condition of *experiment 3* in which the cursor is slowest at 180° (maximum speed of 1.5 cm/s) and fastest at 0° (maximum speed of 4 cm/s). *F*: example search display from a visual search trial in *experiment 4*: 4 target objects (right side pink) and 28 distractors (left side pink). The gray dashed and black solid lines show the gaze and hand paths, respectively, from a single trial.

trial. At the beginning of each trial, a start position (empty green circle, radius 5 mm) appeared at the center of the monitor. Once participants moved the cursor to this location it filled to solid green, and after a delay of 750 ms a fixation cross appeared over it (solid white, width 1.4 cm). Participants were instructed to fixate the cross for 1,000 ms, at which point the target and distractor objects appeared. In all trials, there were 28 distractor objects and 2 target objects, with 15 objects on each side located in cells of a 5 × 3 grid. The size of each cell of the grid was 4 × 4 cm, and the position of each object within the cell was randomly jittered. The distance between the right edge of the left-side grid and the left edge of the right-side grid was 12 cm. The objects were 1.2-cm-wide squares (subtending ~1.9° of visual angle when in the center of the monitor). For the target objects, the right half was colored pink and the left half colored blue. The distractor objects had the opposite color arrangement. The locations of the target objects (i.e., the cells in which the targets appeared) were pseudorandomized such that each target appeared an equal number of times in each cell and a given cell could not contain a target over successive trials. Over the course of the experiment, both targets were on the left side in 25% of the trials, both targets were on the right side in 25% of the trials, and there was one target on either side in 50% of the trials. Thus, by first searching (exhaustively) on the low-effort side, a participant could avoid reaching to the high-effort side in three out of four trials on average. The participant was required to find one of the two target objects and then move the cursor to that target. The trial was considered to have been completed when any part of the cursor overlapped with any part of the target for 100 ms. In the trial shown in Fig. 1*B*, the search time (from the onset of the search stimuli to the onset of the reaching movement) was 3.8 s, during which 10 objects, including one of the targets, were fixated.

A movement time criterion was imposed such that if participants took longer than 2 s to reach the target once they initiated the movement, they would be presented with the phrase "TOO SLOW" in the center of the display and hear an "incorrect" tone (5 Hz, 100 ms) being played. We included this movement time criterion to ensure that participants always experienced fairly significant resistance when velocity-dependent forces were imposed by the handle (see below). To avoid excessive search times, we also implemented a combined search plus movement time criterion such that if the target was not reached within 10 s, participants were presented with the phrase "TIMEOUT" and the same incorrect tone. This time limit was exceeded in only 1% of all trials. If participants completed the trial within these time criteria, they were presented with the phrase "TARGET FOUND" and a "correct" tone (5,000 Hz, 100 ms) was played.

Procedure.

Before beginning the experiment, participants completed an eye calibration procedure followed by five practice trials. The experiment started with 30 baseline trials in which a small viscous (i.e., velocity dependent) load of 10 N·s/m was applied to the handle when reaching to targets on either the left or right side. Note that all viscous forces were resistive and acted in the opposite direction of the motion of the hand. By including these baseline trials, we could measure each participant's initial bias in search behavior. After the baseline trials, participants completed 180 test trials, taking a short rest every 60 trials. In the test trials, we set the viscosity of the load on the higher-effort side to 30 N·s/m while keeping the low-effort side at the baseline value of 10 N·s/m. After the test phase, participants performed an additional block of 30 baseline trials, with viscosity returning to 10 N·s/m on both sides, which we refer to as the washout phase. Note that the difference between the low and high viscosities we used is substantially greater than the just noticeable difference in viscosities reported by Jones and colleagues (29). These authors examined viscosity discrimination during arm movements and reported, for viscosities ranging from 4 to 512 N·s/m, a Weber fraction (the ratio of the just noticeable difference to the intensity of a stimulus) of 19%. Based on this fraction, in our experiment we would expect participants to be able to discriminate between viscosities of 10 and 12 N·s/m at the low end and between viscosities of 30 and 24 N·s/m at the high end. Thus, we would expect that participants should be able to easily discriminate between the two viscosities we used. This is certainly consistent with our own experience with these viscosities; anecdotally, they feel very different.

Experiment 2: Effort Costs in Manual Search

Materials.

Figure 1*C* shows the visual stimuli presented to a participant, as well as the cursor path (black trace) produced by the participant, in a single trial. The locations of distractor objects (blue squares) visited during the trials and the four target objects (pink squares) are indicated. The target and distractor objects were the same size as in *experiment 1* and were located within a circular search area that had a radius of 14 cm around the center of the monitor. Within this circle, 60 objects were arranged by aligning them to a grid that contained 61 cells, with the extra cell containing the start position (green circle). The size of each cell of the grid was 3.5 × 3.5 cm, and the position of each object within the cell was randomly jittered. In each trial, the start position and the four target locations were randomly selected.

At the start of a trial, the participant had to move the cursor to the start position and was asked to fixate the cross that then appeared at that location. Once the cursor was held in the start position for 750 ms, the search objects (all gray squares) appeared and participants had to locate one of the four search targets. To identify whether a given gray search object was a target or a distractor, participants had to bring the cursor to a stop on the object. Specifically, they needed to keep the center of the cursor within 5 mm of the center of the object for 500 ms, after which the search object changed color. If the object was a target, it turned pink, the text "TARGET FOUND" was displayed in the center of the display, a correct tone (5,000 Hz, 100 ms) sounded, and, after a 1-s delay, the trial ended. If the object was a distractor, it turned blue and participants had to continue searching for one of the targets. Once a search object changed color, it remained that way for the duration of the trial, such that participants did not have to memorize the location of already-visited objects. If participants could not locate a target object within 30 s, "TIMEOUT" was displayed on the screen, an incorrect tone (5 Hz, 100 ms) sounded, and, after a 1-s delay, the trial ended. This occurred in <1% of all trials.

Procedure.

Participants were informed before beginning the experiment that there were four search targets on each trial and that their location was determined through randomization. The experimenter demonstrated a trial to familiarize them with the task. Participants completed four blocks of 25 trials each starting with either a force-on or force-off block (counterbalanced across participants) and then alternating between block types, such that all participants experienced two force-on blocks and two force-off blocks. In force-on trials, the manipulandum applied an elastic force to the handle with the force directed back to the start position and increasing linearly with the distance of the cursor from the start position multiplied by the spring constant k = 80 N/m. With the application of this elastic load, the further an object was from the start position the more effort participants needed to expend to visit it. In force-off trials, no external force was applied to the handle (i.e., k was set to 0).

Experiment 3: Time Costs in Manual Search

Materials.

Figure 1*D* shows the visual stimuli presented to a participant, as well as the cursor path (black trace) produced by the participant, in a single trial. The locations of distractor objects (blue squares) visited during the trials and the four target objects (pink squares) are indicated. The size, appearance, and location of the target and distractor objects were the same as in *experiment 2* except that the cursor start location was always in the cell located in the center of the search grid. To reveal the identity of an object, the participant had to keep the center of the cursor within 5 mm of the center of the object for 300 ms. The same feedback as in *experiment 2* was given for either successfully locating the target object or timing out, if the search time exceeded 30 s.

Participants controlled the speed and direction of cursor motion with a virtual joystick simulated with a robot handle. To manipulate the cost of time, the gain between the excursion of the joystick from its central (resting) position and cursor speed was varied as a function of the location of the cursor in the search space. To create a virtual joystick, we simulated, using a very stiff damped spring (6,000 N·s/m stiffness, −4 N/m damping), a circular barrier of radius 1 cm around the home position of the handle. Thus, handle movement was limited to 1 cm in any direction. Additionally, a weak damped spring (300 N·s/m stiffness, −1 N/m damping) generated forces on the handle toward the home position. Thus, if no forces were applied to the handle by the participant, this spring brought the handle back to its home location. These two springs allowed the handle of the manipulandum to effectively function as a joystick. The location of the handle while operating as a joystick was ∼20 cm in front of the participant's chest and in the midsagittal plane.

The cursor's speed depended on the distance and direction of the joystick from its central start position and the current angular location of the cursor according to the following relationship:

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = \begin{bmatrix} J_x \\ J_y \end{bmatrix} \frac{1.25[\cos(\boldsymbol{\theta} - \beta) + 1] + 1.5}{s}$$

where V_x and V_y are the x and y cursor velocities in centimeters per second, J_x and J_y are the x and y joystick positions in centimeters, $\boldsymbol{\theta}$ is the angular position of the cursor, and β is either 0° or 180° in the slow-left and slow-right conditions, respectively. We applied a cosine function to the cursor's angle to allow for a gradual change in cursor speed between the 0° and 180° positions. The perimeter of the blue region in Fig. 1*E* represents the maximum cursor speed (with the joystick at full excursion) as a function of angle in the slow-left condition where the maximum speed is 1.5 cm/s when $\boldsymbol{\theta}$ = 180° and 4 cm/s when $\boldsymbol{\theta}$ = 0°.

In slow-left trials, the maximum speed was greatest when the cursor was located to the right of center (0°, as shown in Fig. 1*E*) and slowest when the cursor was located to the left of center (180°), and these directions were flipped in slow-right trials. The four target objects in a given trial were randomly located, and therefore there was a high probability (P = 0.9375) that at least one target would be located on a given side (left or right). Thus, in principle, participants could reduce the time required to locate a target object (on average) by searching the side of the space associated with faster cursor movements.

Procedure.

Each participant experienced two slow-left blocks of trials and two slow-right blocks of trials, with the two block types alternating. Each block consisted of 25 trials, and the initial block type was counterbalanced across participants. We implemented this alternating block structure because of the possibility that cursor speed might only bias search behavior after experiencing both slow-left and slow-right trials. Before beginning each block, participants completed a single practice trial, where they had to visit each search object location and reveal its identity with the cursor. In this trial, all objects were "distractors" and turned blue when visited. On this single practice trial, cursor behavior was the same as in the upcoming block and participants were told that this would be the case. These practice trials were included so that participants had an opportunity to experience and learn the mapping between joystick motion and cursor speed applied to trials within the upcoming block.

Experiment 4: Time Costs in Visual Search

Materials.

In this experiment, before testing participants on a visual search task that incorporated movement time costs, we first tested them on a manual search version of the task so that they would have the opportunity to learn about the costs associated with moving in different regions of the search space. In both versions of the task, target and distractor objects were presented within a circular search area that had a radius of 11.4 cm around the center of the monitor (Fig. 1*F*). Within this circle, we arranged 32 search objects by aligning them to a grid containing 33 cells, with the extra cell containing the start position at the center. The size of each cell of the grid was 3.8 × 3.8 cm. There were four search targets in each trial, and the method for selecting target locations was the same as that described in *experiment 3*.

The search objects in visual search trials were split color squares (width 1 cm; ∼1.6° visual angle) with one half pink and the other half blue (as shown in Fig. 1*F*). The target objects had the opposite color arrangement to the distractor objects. The search objects in the manual search trials were gray squares (also width 1 cm), and the participant could identify a square as either a target or a distractor by holding the cursor over its location, at which point the object color changed to either pink (target) or blue (distractor).

In both visual and manual search trials, participants controlled the cursor, which was positioned in the center of the search space at the start of each trial, by applying forces to a simulated joystick as described for *experiment 3*. In manual search trials, participants were instructed to move the cursor to search objects and hold the cursor over the object to reveal its identity. In visual search trials, participants were instructed to move the cursor to the target once it had been visually located and hold the cursor at that location to end the trial. The hold criterion for the target in visual search trials was identical to the hold criterion for revealing a search object's identity in the manual trials, which is fully described in the methods for *experiment 3*. In visual search trials, participants were required to fixate the start position at the start of the trial.

The dependence of cursor speed and joystick position and the current angular location of the cursor was the same as in *experiment 3*, with the maximum cursor speed being faster on either the left or right side of the search space in different blocks of trials (see below). As in *experiment 3*, there was a high probability (P = 0.9375) that at least one target would be located on a given side (left or right). Thus, in principle, the time required to reach a visually located target object (visual search), or manually locate a target object (manual search), could be reduced by searching the side of space associated with faster cursor movements. The feedback given for successfully locating the target object, or timing out, was the same as in *experiments 2* and *3*.

Procedure.

All participants completed four blocks of 25 trials. Participants first performed a block of manual search trials and then a block of visual search trials with the slow side either on the left or right (counterbalanced across participants) in both blocks. After these two blocks, they performed a block of manual search trials and then a block of visual search trials with the slow side on the opposite side. After completing a block of manual search trials, participants were explicitly informed that the relationship between cursor location and speed would be the same on the subsequent block of visual search trials. Before beginning each manual search block, participants completed a practice trial, as in *experiment 3,* where the cursor's behavior was the same as in the upcoming block of trials. These practice trials were included so that participants had an opportunity to experience and learn the joystick-to-cursor mapping applied to trials in the upcoming block of manual trials.

RESULTS

Experiment 1: Effort Costs in Visual Search

The aim of *experiment 1* was to assess whether movement effort influences visual search using a "search-and-then-reach" task. Effort was manipulated by applying large resistive forces to the hand when moving on one side of the search space (Fig. 1*B*) but not the other. Recall that in this experiment there were two randomly located target objects. Therefore, by first exhaustively searching the low-effort side of the search space, a participant could avoid reaching to the high-effort side in 75% of the trials. Figure 2, *A* and *B*, shows the peak force applied to the hand and peak hand velocity for movements to targets on the low- and high-effort sides of space. As expected, peak forces were far greater for movements on the high-effort side [$t(10) = 22.56$, $P < 0.001$, $d = 6.25$]. Peak velocity was slightly but significantly smaller for movements on the high-effort side [$t(10) = 5.82$, $P < 0.001$, $d = 1.33$].

Figure 1*B* shows the gaze and cursor paths for a single baseline trial from one of our participants. In this trial, the search time (from the onset of the search stimuli to the onset of the reaching movement) was 3.8 s, during which 10 objects, including one of the targets, were fixated. Across participants, the average trial search time, based on participant means, was 2.8 s (SE = 0.09 s) and the corresponding average number of objects fixated was 5.8 (SE = 0.3). As exemplified in Fig. 1*B*, during visual search participants tended to make small saccades when shifting gaze from one object to the next. Figure 2*C* shows the distribution of distances between successively visited (i.e., foveated) objects during the test phase. The peak of the distribution closely corresponds to the distance between adjacent objects in the same row or column (left dashed vertical line). Note that the average distance between objects, in the same row, in the rightmost and leftmost columns of the left and right sides of the search space, respectively, was 16 cm. Thus, saccades between objects on opposite sides of the search space would have distances of ∼16 cm or larger and occurred relatively infrequently. On average, during the test phase participants made a saccade from one side of the search space to the other in 37.4% (SE = 2.0%) of all trials. Had participants always exhaustively searched one side before switching to the other side if necessary, such saccades would have occurred in 25% of all trials.

Given our hypothesis that increased motor effort would bias search behavior, we were primarily interested in to which side of the search space participants directed their gaze during search. Therefore, for each trial, we first computed the average *x*-location of each fixation before reach onset, where the *x*-location of the center of the search space is 0 (Fig. 1*B*), and multiplied this location by the duration of the fixation. We then summed up these values, across the fixations in the trial, and divided by the total fixation duration in the trial to normalize across trials of varying search duration. Finally, we signed this location as positive or negative depending on whether it was on the low-effort or high-effort side, respectively. We refer to this measure as the "integrated

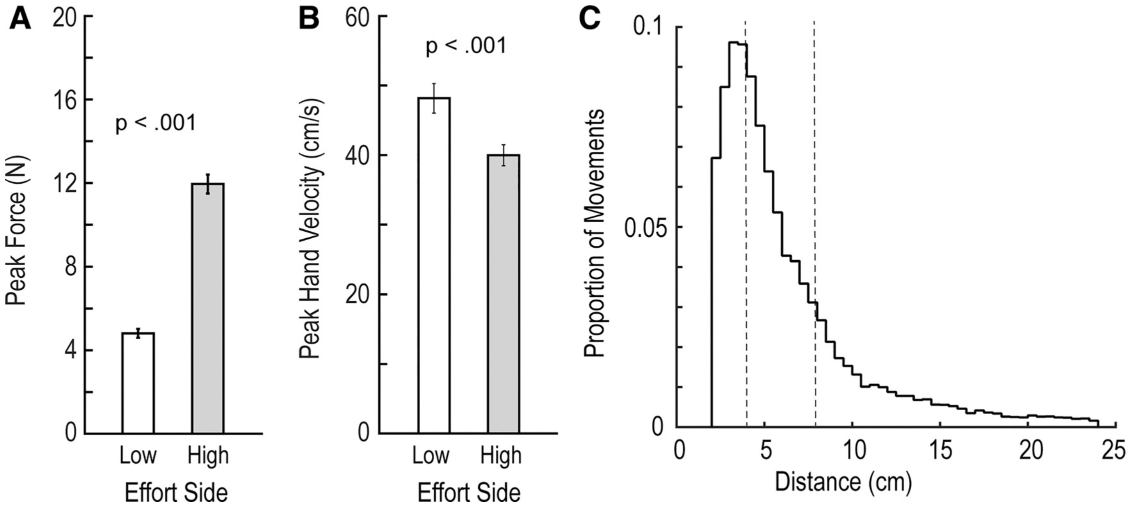

Figure 2. Participants' movements required more force generation, and were slower, on the high-effort side of space. *A*: peak forces applied to the hand by the handle during reaches to target objects located on the high- and low-effort sides of the search space. *B*: corresponding peak hand velocities of these reach movements. Error bars indicate ±1 SE. *C*: frequency distributions of the distance between successively visited objects during the test phase. The first vertical dashed line shows the average distance (*d*) between adjacent objects, and the second line shows the average distance (2*d*) between next-to-adjacent objects in the same row or column.

gaze location," with positive values indicating that gaze was biased toward that low-effort side (i.e., the side requiring less effort in the test phase) and negative values indicating that gaze was biased toward that high-effort side. More formally, we defined the integrated gaze location as

$$\text{integrated gaze location} = \frac{b\sum_{i=1}^{N}\bar{x}_i d_i}{\sum_{i=1}^{N} d_i}$$

where $\bar{x}_i$ and d_i are the mean x-position and duration of the ith fixation in a trial and b is -1 or $+1$ depending on whether the low-effort side is on the left (negative x) or right (positive x) side of the search space. Note that when computing the integrated gaze location in baseline trials we defined the low- and high-effort sides based on the low- and high-effort sides from the (later) test phase experienced by the participant, allowing us to remove any baseline bias. We assessed other measures to evaluate gaze bias, including the proportion of fixations on the force minimum side and the proportion of time spent fixating the force minimum side. Because all of these measures revealed very similar patterns of results, we opted to only report the results for the integrated gaze location.

Figure 3*A* shows the relationship, across participants, between the average integrated fixation location in baseline and test trials. Each circle represents a single participant, and, as noted above, positive values indicate a bias to searching on the low-effort side. Our hypothesis predicts that the data points (i.e., participants) should fall above the unity line ($x = y$). That is, independent of whether a participant was biased to the high- or low-effort side during the baseline phase (i.e., the side that became the high- or low-effort side during the test phase), they should become more biased toward the low-effort side during the test phase. Most participants were close to the unity line, and, across participants, the average integrated fixation locations in the baseline and test trials were highly correlated (r = 0.92, $P < 0.001$). This finding indicates that participants generally did not alter their search behavior from the baseline phase to the test phase.

Figure 3*B* shows the mean integrated fixation location, averaged across participants, during the baseline, test, and washout phases. For each phase, separate bars are shown for each location (left or right) of the low-effort side. Overall, a clear left side bias was observed such that participants tended to search on the low-effort side when the low-effort side was on the left (open bars) and on the high-effort side when the high-effort side was on the left (filled bars). A phase (baseline, test, washout) × high-effort side (left, right) mixed-model analysis of variance (ANOVA) revealed an effect of high-effort side [$F(1,9)$ = 10.94, P = 0.009, η^2 = 0.549] on integrated fixation location but failed to reveal an effect of phase [$F(2,18)$ = 0.104, P = 0.903] or an interaction between high-effort side and phase [$F(2,18)$ = 0.451, P = 0.644]. Note that our main hypothesis predicted that there would be an effect of phase. However, this effect was not observed.

Another way to assess search bias is to examine which target participants reached for in trials in which there was a target on each side. Figure 3*C* shows the proportion of reaches

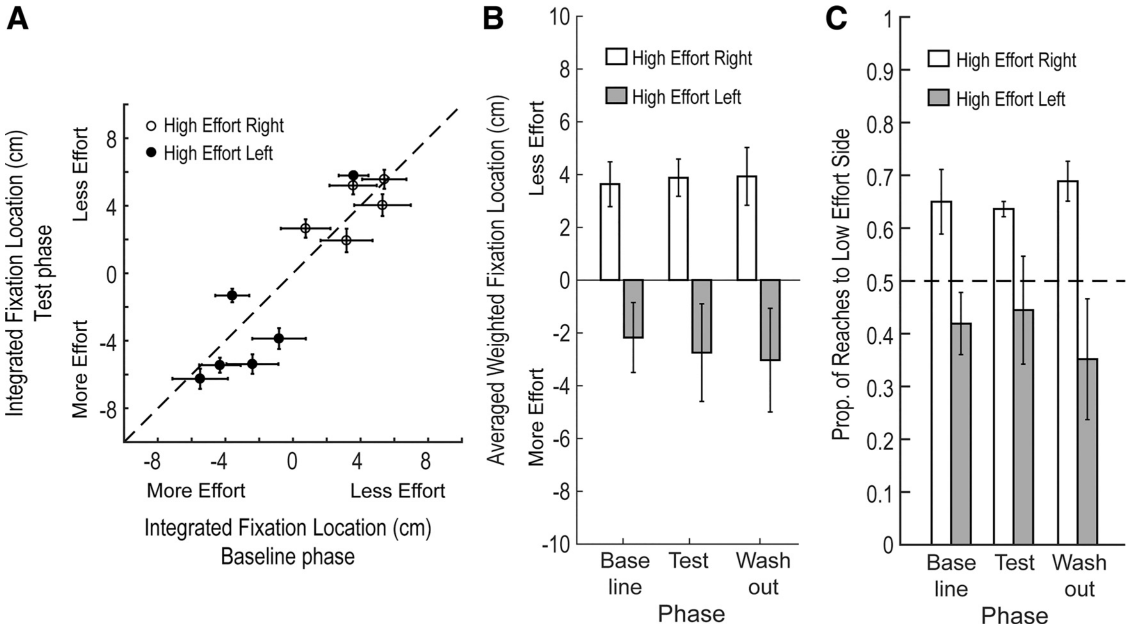

Figure 3. *A*: integrated fixation location in the test phase plotted against the integrated fixation location in the baseline phase. Each circle represents the mean of a single participant, and the error bars represent ±1 SE. Filled and open circles indicate that the location of the high-effort side was on the left and right, respectively. Positive values indicate that the integrated fixation location was on the low-effort side of the search space. Values located above the dashed unity line indicate that during the test phase the participant shifted their search bias toward the low-effort side relative to the baseline phase. *B*: average integrated fixation location based on participant means. For each phase of the experiment, separate bars are shown for the different load conditions and the location of the high-effort side, with positive values indicating fixations were biased to the low-effort side. *C*: proportion of reaches to the low-effort side during trials in which there was 1 target on each side of the screen. Separate bars are shown for the 2 load conditions and, for each condition, the location of the high-effort side. The dashed horizontal line represents the proportion of reaches expected if participants were selecting a side at random. *B* and *C*: bars represent participants' means, and the error bars indicate ±1 SE.

to the low-effort side in each phase (i.e., baseline, test, washout) of the experiment. Separate bars are shown for each location (left or right) of the high-effort side. It can be seen that for each high-effort side the proportion of reaches to the low-effort side was quite consistent across the phases of the experiment. Consistent with the left side search bias described above, reaches tended to be biased toward the left side of space such that participants tended to reach to the low-effort side when the low-effort side was on the left (open bars) and on the high-effort side when the high-effort side was on the left (filled bars). To quantitatively assess this pattern of effects, we performed a phase (baseline, test, washout) × high-effort side (left, right) mixed-model ANOVA. Consistent with the gaze analysis above, this analysis revealed a main effect of high-effort side [$F(1,9) = 6.713$, $P = 0.029$, $\eta^2 = 0.427$] but failed to reveal a significant main effect of phase [$F(2,18) = 0.097$, $P = 0.908$] or an interaction between high-effort side and phase [$F(2,18) = 1.291$, $P = 0.299$]. Again, note that our main hypothesis predicted that there would be an effect of phase.

The results of this initial experiment did not support our hypothesis that visual search behavior would be influenced by effort costs associated with reaching to targets once they have been located. Specifically, we observed that participants did not tend to alter their search behavior after forces were introduced that made one side of the search space more effortful to reach in than the other side. A possible explanation for this outcome is that participants selected a side to search early on during the baseline phase and then did not deviate from this strategy. However, some participants did not exhibit a strong bias toward any given side. Another possibility for why movement costs were not factored into account is that they were incurred well after decisions about where to search were made. Recent work on sensorimotor decision making has shown that both effort costs and rewards are temporally discounted, such that their influence diminishes with the delay between when decisions are made and when the costs or rewards are incurred (30–32). It is also possible that our participants simply did not find the load experienced on the handle to be adversive, perhaps because the load was only experienced for a relatively short duration and intermittently.

Experiment 2: Effort Costs in Manual Search

The aim of *experiment 2* was to examine whether effort costs that are incurred during search influence search behavior. Participants moved the handle of a manipulandum to move a cursor to objects in a display to reveal whether the object was a target or a distractor (Fig. 1*C*). An elastic force was applied to the handle such that the force acting on the hand increased linearly with the distance of the handle from the start position and was directed toward the start position. Thus, greater effort was required to move the cursor to objects located farther from the start. Across blocks of trials, participants searched for a target object with the elastic force turned either on or off.

Figure 1*C* shows the cursor path, the objects visited, and the locations of the four targets (shown in pink) for a single trial in which 18 objects (including the target found) were visited. On average, the search time across participants was 14.9 s (SE = 0.4 s) in force-off trials and 15.3 s (SE = 0.3 s) in force-on trials. In force-off trials participants visited an average of 11.9 (SE = 0.3) objects before locating the search target, and the average in force-on trials was 11.7 (SE = 0.2). There was no significant difference between force-on and force-off trials in terms of search time [$t(15) = 0.809$, $P = 0.431$] or the number of objects visited to locate a search target [$t(15) = 0.433$, $P = 0.671$]. During manual search participants tended to make small movements when moving from one object to the next. Figure 4*A* shows the distributions of distances between successively visited objects for all force-on and all force-off trials. The peaks of the distributions correspond to the distance between adjacent objects in the same row or column (left dashed vertical line), and the large majority of movements were to an adjacent object.

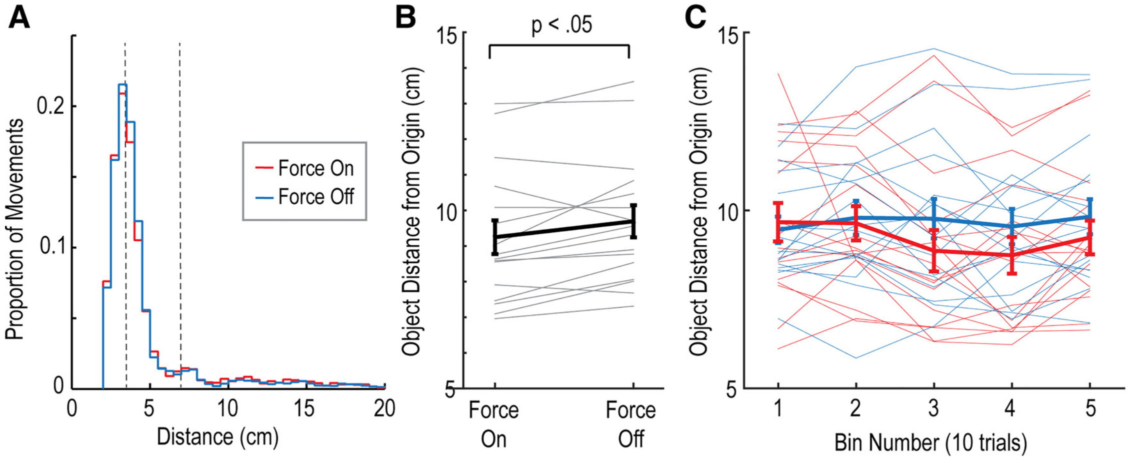

Figure 4. *A*: separate frequency distributions, for force-on (red) and force-off (blue) trials, of the distance between successively visited objects (combining data from all participants). The first vertical dashed line shows the average distance (*d*) between adjacent objects in the same row or column, and the second line shows the average distance (2*d*) between next-to-adjacent objects in the same row or column. *B*: average distance from the origin of objects visited across trials for blocks with the elastic force on and blocks without. Individual participants are shown in gray traces. *C*: average distance from the origin in force-on (red) and force-off (blue) trials for each successive bin of 10 trials. Thin lines represent individual participants. *B* and *C*: error bars indicate ±1 SE.

We predicted that participants would, on average, visit object locations closer to the start position in force-on trials in comparison to force-off trials. To assess this prediction, we determined, for each participant, the mean average distance of the targets visited from the start position across trials for each of the four trial blocks. To investigate the effects of block type (force on vs. force off) and block number (first or second), we ran a 2 × 2 repeated-measures analysis of variance (rmANOVA) with average target distance as the dependent variable. This analysis revealed an effect of block type [$F(1,15) = 7.34$, $P = 0.016$, $\eta^2 = 0.329$] but no effect of block number [$F(1,15) = 2.20$, $P = 0.159$] and no interaction between block type and block number [$F(1,15) = 0.287$, $P = 0.161$]. The thick line in Fig. 4*B* shows the group means of the average target distance for all force-on trials and all force-off trials (collapsing across block numbers because there was no main effect of block). The thin gray lines represent individual participants. We found that participants in force-off trials (mean = 9.69 cm, SE = 0.45) visited objects that were, on average, 0.44 cm further away from the start position than in force-on trials (mean = 9.25 cm, SE = 0.47). These results indicate that although participants tended to search significantly closer to the start position in force-on trials, the effect was small. That is, 0.44 cm is considerably less than the average x or y distance between adjacent targets (3.5 cm).

To examine how the force bias evolved across trials, we determined, for each participant and trial type (force on and force off), the mean average distance from the start position across trials for each successive bin of 10 trials (resulting in 5 bins across the 2 blocks of 25 trials for each trial type). As shown in Fig. 4*C*, the force bias only emerged after the first two bins of trials and appeared to involve a reduction in average distance in force-on trials. Paired t tests revealed a significant effect of trial type for *bins 3* [$t(15) = 2.30$, $P = 0.036$] and *4* [$t(15) = 3.37$, $P = 0.004$], a marginally significant effect in *bin 5* [$t(15) = 2.12$, $P = 0.051$], but no effect in *bins 1* [$t(15) = -0.45$, $P = 0.66$] and *2* [$t(15) = 0.46$, $P = 0.65$]. These results suggest that participants had to gain experience moving in the force-on environment before the environment began to influence search behavior.

There are a number of factors that may have contributed to the finding that effort had a significant, albeit small, influence on search behavior in *experiment 2* but not in *experiment 1*. First, participants experienced higher peak forces on the handle of the manipulandum in *experiment 2* compared to *experiment 1*. On average, in a given trial, participants in *experiment 2* experienced a peak force of 21.0 N (SE = 0.4) on the handle, whereas the average peak in *experiment 1* was 12.0 N (SE = 0.5). Second, whereas participants in *experiment 1* only experienced forces during a short-duration point-to-point movement, participants in *experiment 2* experienced these forces over a longer time period when they were visiting and holding the handle over objects during search. Third, whereas movement costs were experienced during the search process itself in *experiment 2*, movement costs were experienced after search was completed in *experiment 1* and therefore may have been temporally discounted (30–32). The greater and longer-lasting forces experienced in *experiment 2* may have led to participants becoming fatigued, and it has been shown, in several tasks, that fatigue can be a motivating factor in making movement decisions that will reduce effort (33, 34).

Experiment 3: Time Costs in Manual Search

The previous experiments examined whether movement effort can influence search behavior during the performance of visual and manual search tasks. Given that movement time costs have been found to influence choice behavior in humans (30, 31), in *experiment 3* we investigated whether movement time costs can influence search behavior in a manual search task. Participants moved a cursor from a central start position to objects and had to hold the cursor over an object to reveal whether it was a target or a distractor. Figure 1*D* shows the cursor path produced by the participant in a single trial. The locations of distractor objects (blue squares) visited during the trials and the four target objects (pink squares) are indicated. Participants controlled the speed and direction of cursor motion using a virtual joystick simulated with a robot handle. During search participants tended to make small movements when moving between objects. Figure 5*A* shows the distributions of distances between successively visited objects for all slow-left and slow-right trials. The peaks of the distributions correspond to the distance between adjacent objects in the same row or column (left dashed vertical line), and the vast majority of movements were to an adjacent object.

To manipulate the cost of time, the gain between the excursion of the joystick from its central (resting) position and cursor speed was varied as a function of the angular location of the cursor in the search space. Figure 1*E* shows this mapping for "slow-left" trials in which the maximum cursor speed (with full joystick excursion) was smallest when the cursor was directly to the left of the start position (180°). In "slow-right" trials the maximum cursor speed was smallest when the cursor was directly to the right of the start position (0°). Each participant completed two slow-left trial blocks and two slow-right trial blocks in alternation. Each block consisted of 25 trials, and the initial block type was counterbalanced across participants. Recall that in this experiment there were four randomly located target objects. Therefore, by first exhaustively searching the low-effort side of the search space, a participant could avoid reaching to the high-effort side in ∼94% of the trials. We observed no significant difference between slow-left and slow-right trials in terms of search time [$t(11) = 0.726$, $P = 0.483$] or the number of objects visited [$t(11) = 0.112$, $P = 0.913$]. Overall, the average search time was 18.7 s (SE = 0.48) and the average number of objects visited was 9.9 (SE = 0.29).

To investigate the influence of movement time on participants' search behavior, we looked at both the angle and x-location of objects visited across block types. Figure 5*B* shows a polar probability density plot of the location of objects visited for each block type. It can be seen that participants tended to visit objects on the side associated with faster cursor movements, with most of the visited objects located within 60° of the angle associated with the fastest cursor speed (i.e., a region where the maximum cursor speed was at least 84% of the fastest cursor speed).

To further assess the influence of movement time on search behavior, for each participant we computed the

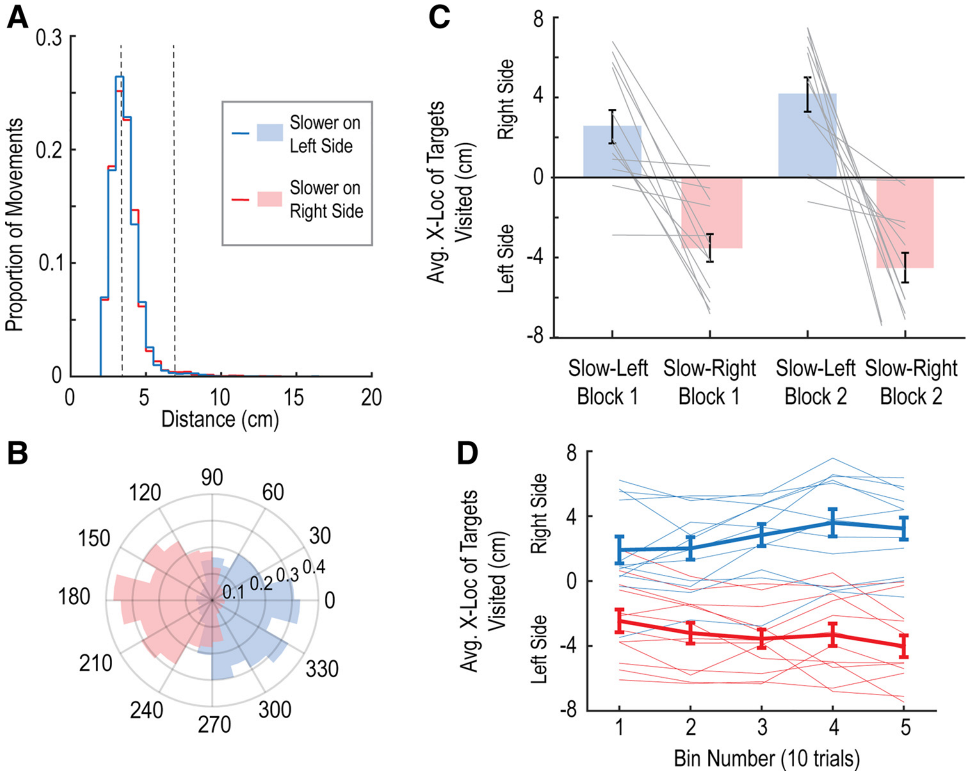

Figure 5. *A*: separate frequency distributions, for slow-left (blue) and slow-right (red) trials, of the distance between successively visited objects (combining data from all participants). The first vertical dashed line shows the average distance (*d*) between adjacent objects in the same row or column, and the second line shows the average distance (2*d*) between next-to-adjacent objects in the same row or column. *B*: polar plot showing the probability density, combining all data from all participants, of the angular locations of objects visited by the cursor during search (15° bins). In the slow-left (blue) and slow-right (red) conditions, participants tended to visit objects on the right and left sides of the search space, respectively. *C*: average *x*-location of objects visited by the cursor in each trial block. Positive values indicate locations to the right of midline. Gray lines represent individual participants. *D*: average distance from the origin in slow-left (blue) and slow-right (red) trials for each successive bin of 10 trials. Thin lines represent individual participants. *C* and *D*: error bars indicate ±1 SE.

average x-location of objects visited in each trial and then determined the average for each trial block. Figure 5*C* shows the average x-location of objects visited in the first and second blocks of slow-left and slow-right trials. To investigate the effects of the block type (slow left vs. slow right) and block number (first or second), we ran a 2 × 2 repeated-measures analysis of variance (rmANOVA) with the average x-location of objects visited as our dependent variable. This analysis revealed an effect of block type [$F(1,11) = 27.93$, $P < 0.001$, $\eta^2 = 0.717$] but no effect of block number [$F(1,11) = 0.44$, $P = 0.519$, $\eta^2 = 0.039$]. However, there was an interaction between block type and block number [$F(1,11) = 11.10$, $P = 0.007$, $\eta^2 = 0.502$]. The significant interaction was driven by a larger difference between block types (i.e., slow-left vs. slow-right trials) in the second block of trials (8.65 cm) compared to the first block of trials (6.05 cm). Follow-up paired t tests revealed significant effects of block type in both the first block [$t(11) = 4.81$, $P = 0.001$, $d = 2.19$] and the second block [$t(11) = 5.37$, $P < 0.001$, $d = 2.98$], which remain significant when corrected with the Holm–Bonferroni method. Taken together, these results suggest that participants searched in areas associated with higher cursor speed, and hence lower time costs, and that this bias increased as participants gained experience with the task and became more familiar with the search environment.

To examine how the search bias evolved across trials, we determined, for each participant and trial type (slow left and slow right), the average x-location of objects visited in each successive bin of 10 trials (resulting in 5 bins across the 2 blocks of 25 trials for each trial type). As shown in Fig. 5*D*, the bias appeared to increase over the first three bins but was present throughout the experiment. Paired t tests revealed a significant effect of trial type for all five bins ($P < 0.004$ in all 5 cases). These results suggest that the initial practice trials in which participants experienced the slow-left and slow-right environments was sufficient to give rise to the bias. However, the bias nevertheless increased as participants gained experience moving in the two environments.

The fact that participants' search was biased to the side of the search space associated with a higher maximum cursor speed does not necessarily imply that they actually shortened their search times. Specifically, it is possible that participants did not take advantage of the faster cursor speed. To examine the speed at which participants searched, for each participant we calculated the average duration (across all trials) of cursor movements between search objects located on the fast side of the search space and between search objects located on the slow side (we did not consider movements between objects located on opposite sides of midline). We found that movement durations were significantly shorter [$t(11) = 10.09$, $P < 0.001$, $d = 3.68$] for cursor movements between fast-side objects (mean = 1.09 s, SE = 0.02) than between slow-side objects (mean = 1.69 s, SE = 0.06). This result indicates that participants exploited the variable cursor speed to reduce their search times.

The results of this experiment are consistent with previous work that has found that people incorporate kinematic factors such as movement time and effort, as well as object size and distance (which influence movement time), when deciding between movement options (15, 16, 35). Our present results suggest that the influence of movement time costs extends to decisions involved in search, which are traditionally considered to be more cognitive in nature.

Experiment 4: Time Costs in Visual Search

The aim of *experiment 4* was to test whether movement time costs influence visual search when participants are required to move a cursor to the target once it has been visually located. As in *experiment 3*, participants used a virtual joystick to control the cursor. The mapping between cursor angular position and maximum cursor speed was the same as in *experiment 3*, and, again, the maximum speed could be smallest when the cursor was either to the left (slow-left trials) or right (slow-right trials) of the central start position. Participants first performed a block of manual search trials and then a block of visual search trials with the slow side either on the left or on the right in both blocks. After these two blocks, they performed a block of manual search trials and then a block of visual search trials with the slow side on the opposite side. Participants were told that the relationship between cursor location and speed in each block of visual search trials would be the same as in the preceding block of manual search trials. We had participants perform alternating blocks of manual and visual search trials so that they would be familiar with the mapping while performing the visual search trials.

In visual search trials, the objects were split-color squares with the four targets (Fig. 1*F*) having opposite patterns to the distractors. In the manual search trials, the objects were gray squares that turned either blue (distractor) or pink (target) when visited by the cursor. Figure 1*F* shows the gaze (dashed line) and cursor (solid line) path produced by a participant in a single trial. In both visual and manual search trials, there were four randomly located target objects. Therefore, by first exhaustively searching the low-effort side of the search space, a participant could avoid reaching to the high-effort side in ∼94% of the trials.

As in *experiment 3*, during manual search trials participants tended to make small movements when moving between objects. The thin lines in Fig. 6*A* show the distributions of distances between successively visited objects for all slow-left and slow-right manual search trials. The large majority of movements were to an adjacent target; the left dashed vertical line in the figure represents the distance between adjacent objects in the same row or column. The same basic pattern was observed in visual search trials. However, participants were more likely to shift their gaze to nonadjacent objects, which may be due to the

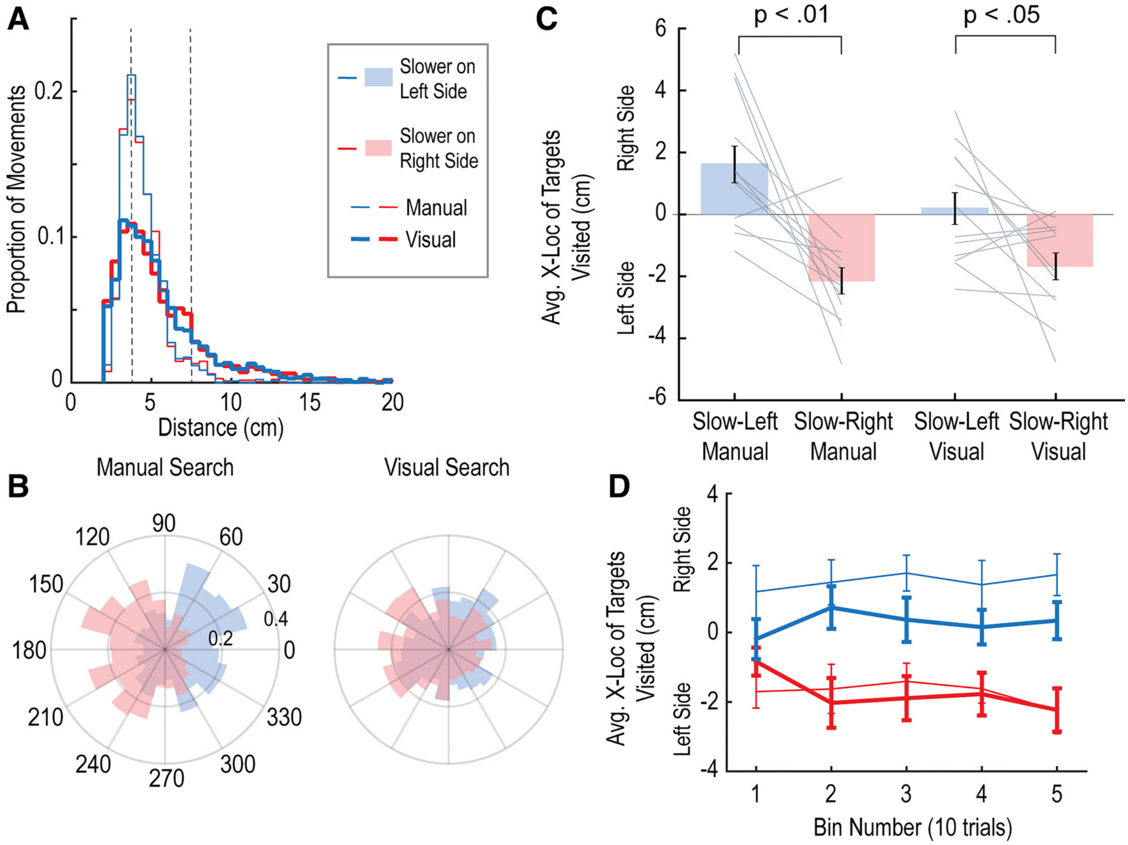

Figure 6. *A*: separate frequency distributions, for slow-left and slow-right manual and visual search trials, of the distance between successively visited objects (combining data from all participants). The first vertical dashed line shows the average distance (*d*) between adjacent objects in the same row or column, and the second line shows the average distance (2*d*) between next-to-adjacent objects in the same row or column. *B*: polar plots showing the probability density, combining all data from all participants, of the angular locations (15° bins) of objects visited by the cursor or gaze during manual and visual search, respectively. In the slow-left (blue) and slow-right (red) conditions, participants tended to visit objects on the right and left sides of the search space, respectively, but this effect was more pronounced in manual search than in visual search. *C*: average *x*-location of objects visited by the cursor in manual search trials (*left*) and fixated in visual search trials (*right*). Positive values indicate locations to the right of midline. Gray lines represent individual participants. *D*: average distance from the origin in slow-left and slow-right manual and visual search trials for each successive bin of 10 trials. *C* and *D*: error bars indicate ±1 SE.

lower energy cost of generating eye movements compared with hand movements (36).

We predicted that participants would learn the relationship between cursor speed and angle during the manual search trials and demonstrate a manual search bias toward the side of space with faster cursor speeds. We further predicted that they would subsequently demonstrate a bias toward searching the side of space associated with faster cursor speeds in the following visual search trials.

For manual search blocks, there was no significant difference in search time between slow-right (mean = 15.6 s, SE = 0.9) and slow-left (mean = 15.8 s, SE = 0.7) trials [$t(11) = 0.161$, $P = 0.875$]. Likewise, for visual search blocks, there was no significant difference in search time between slow-right (mean = 5.8 s, SE = 0.2) and slow-left (mean = 6.1 s, SE = 0.2) trials [$t(11) = 1.34$, $P = 0.207$].

We examined, for each participant, the average *x*-location of objects contacted by the cursor in manual search trials or fixated in visual search trials. Figure 6*B* shows polar probability density plots of the location of objects visited by the cursor during manual search and by gaze during visual search. A clear bias toward visiting objects on the fast side (i.e., the side associated with faster cursor movements) can be seen for manual search. However, this bias is much weaker for visual search. Figure 6*C* shows, for both manual and visual search trials, the average *x*-location of visited objects for slow-left and slow-right trials. In manual search trials, on average search was biased toward the "fast" side of the search space. In visual search trials, search was biased toward the fast side when that side was on the left (slow-right trials), but no clear bias was observed when the fast side was on the right (slow-left trials). One explanation for this pattern of results is that, in visual search, there is both a bias toward search on the left and a bias toward searching on the fast side.

To examine the influence of block type on manual and visual search behavior, we conducted a 2 (block type: slow left, slow right) × 2 (search type: manual, visual) rmANOVA. The analysis revealed a significant effect of block type [$F(1,11) = 14.70$, $P = 0.003$, $\eta^2 = 0.572$] but not search type [$F(1,11) = 4.06$, $P = 0.069$, $\eta^2 = 0.270$], whereas the interaction between search type and block type approached significance [$F(1,11) = 4.61$, $P = 0.055$, $\eta^2 = 0.295$]. Follow-up paired *t* tests revealed significant differences between block type for both manual [$t(11) = 4.08$, $P = 0.002$, $d = 2.01$] and visual [$t(11) = 2.37$, $P = 0.037$, $d = 1.08$] search trials, which remained significant when corrected with the Holm–Bonferroni method. Note that the effect size (Cohen's *d*) was approximately twice as large for manual search compared with visual search. Together with the near-significant interaction between block type and search type, this suggests that the effect of movement time costs may be greater in manual search than in visual search.

To examine how the search bias evolved across trials, we determined, for each participant, trial type (slow left and slow right), and search mode (visual and manual), the average *x*-location of objects visited in each successive bin of 10 trials. The results for manual search were similar to those observed in *experiment 3*. Specifically, paired *t* tests revealed a significant effect of trial type for all five bins ($P < 0.02$ in all 5 cases). For visual search, paired *t* tests revealed a significant effect of trial type for the last four bins ($P < 0.048$ in all 4 cases) but not the first bin ($P = 0.385$). This suggests that some experience performing visual search trials, following manual search trials with the same movement cost structure, was required for participants to appreciate (or be concerned about) movement costs.

Our finding that manual search is biased by movement time costs (associated with cursor speed) replicates the results obtained in *experiment 3*. Our finding that visual search can also be biased by cursor speed can be contrasted with the results of *experiment 1*, in which movement effort cost did not influence visual search. This suggests that time cost may be more aversive than effort cost, at least as implemented in our experiments.

DISCUSSION

Converging evidence from a number of studies suggests that movement costs, such as effort or time, can influence the decisions we make during the performance of action tasks (14–16, 21, 35, 37, 38). In this article we have examined how movement costs incurred either in the act of searching (manual search) or when reaching to a target once it is visually located (visual search) influence search behavior. Across four experiments we tested whether search behavior is biased by motor costs by varying effort or time costs across the search environment. We were interested in whether participants would take these costs into account while searching such that they would bias their search to areas of the search environment that reduced movement effort or movement duration.

In *experiment 1*, we examined whether search behavior in visual search is biased by motor effort and failed to find an effect. In *experiment 2*, we asked whether search behavior in a manual search task can be biased by motor effort and did demonstrate a small effect of effort. In *experiment 3*, we tested the influence of movement time costs on search behavior in a manual search task and found a strong effect. Finally, in *experiment 4*, we examined whether movement time costs bias search behavior in a visual search task and found that these costs did influence search behavior. To summarize, we demonstrated that effort-based costs have an overall weak influence on human search behavior, with a small influence on manual search behavior but none on visual search behavior. In contrast, time-based costs appear to have a strong influence on manual search but also influence visual search. Thus, the present study shows that movement time and effort costs can influence human search behavior, at least in some contexts.

Previous work has shown that movement costs are factored into human decision making across a variety of tasks. For example, it has been shown that movement costs can influence the choice of hand (left or right) used to perform a target-reaching task (37), the choice of which target to reach toward (16, 38), the extent to which people opt to rely on memory during search (24–26), and perceptual judgment tasks (21). The novel contribution of the present work is the demonstration that movement costs can influence both visual search when participants reach to the target object after locating it and manual search when participants make reaching movements to objects to determine which is the target.

Given our results showing that movement-related costs influence search behavior, the question arises as to the potential role of sensorimotor processes in search decision making. It has been argued that, when presented with competing movement options (e.g., potential reach targets), the brain generates sensorimotor representations of these options, in parallel, before selecting one to execute (39–50). Moreover, it has been suggested that these sensorimotor representations may be involved in determining motor costs, associated with different movement options, that can be taken into account when deciding which option to execute (51). Although it seems implausible that the brain would generate sensorimotor representations of the many objects presented in our search tasks, it is conceivable that the movement-related costs associated with different regions of the reachable search space are encoded in sensorimotor areas. Recent work (52) has shown that viewing reachable-scale environments, or "reachspaces," elicits preferential activity in several brain regions that are distinct from regions that prefer views of scenes and objects. These areas, posterior collateral sulcus, dorsal occipitoparietal cortex, and the superior parietal lobule, have been linked to processing the reachability of objects (53, 54), the planning of object-directed hand movements (55), and encoding the weight of an object when planning to lift the object (56). Thus, these areas would be candidates for representing the mapping between movement-related costs and regions within the reachable search space.

In *experiment 1* we failed to find an influence of resistive force on search behavior, despite previous work that found that such forces have the capacity to bias perceptual decision making (19). One possible source of this discrepancy could be the amount of fatigue participants experienced through exposure to forces (33). In the test phase of *experiment 1*, resistive forces were only experienced during the reach at the end of the trial and participants performed a total of 180 trials. In contrast, participants in the Hagura et al. (19) study completed nearly five times as many trials with loads applied. It is possible that in their experiment participants became fatigued, which could have made forces more salient. In *experiment 2*, participants completed 50 search trials with the spring load applied to their hand, and we found that the bias in search behavior, relative to trials without a force applied, emerged after 20 trials. Although this change in bias may have been related to fatigue, it is also possible that participants required experience moving in the search space to appreciate the relationship between their search strategy and movement-related costs.

It is possible that search behavior in everyday search tasks in familiar environments is more strongly influenced by movement costs than in our laboratory tasks. Consider, for example, searching for your cell phone at home. In this case, you have ample opportunity to learn the costs associated with moving in the search environment. In contrast, participants in our experiments had no previous experience with the cost structure of the search environment. Nevertheless, it is clear from *experiments 2*, *3*, and *4* that participants were able to learn the cost structure of the search when performing manual search and, moreover, that this learning could transfer to visual search.

In our tasks, the forces we applied to the handle of the manipulandum, and the speed limits we placed on cursor motion, were quite artificial manipulations of movement effort and movement time, respectively. It is possible that in more ecological tasks, where movement costs are manipulated in a less artificial manner, we would see a larger influence of movement costs on participant behavior. In future work, we plan to examine other ways of manipulating movement effort and time costs that may be more naturalistic. For example, we could place an obstacle in the search space during a visual search task in which participants reach to a target once it is found and ask whether search is biased away from the regions where reaching to a target would require moving around the obstacle. Given the presence of obstacles in our everyday environment, it is possible that participants can readily take such movement costs into account when making decisions about where to search.

The present findings show the importance of factoring movement costs into our understanding of real-world search behavior. Future studies would benefit from more closely examining the relationship between rewards, costs, and memory limitations that may influence real-world search and other action tasks. Our study adds to the growing body of evidence that factors impacting on the motor system, which is often viewed as the final output step in producing behavior, can also influence perceptual and cognitive processes related to decision making during task performance.

DATA AVAILABILITY

The data and analysis code for all of the experiments described in this article will be made available (in the form of MAT files and MATLAB code) on request to the corresponding authors.

ACKNOWLEDGMENTS

We thank Martin York for programming and hardware support.

GRANTS

This work was supported by the Canadian Natural Sciences and Engineering Council (NSERC) and Canadian Institutes of Health Research (CIHR).

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

J.B.M., S.A.B., M.S.C., J.P.G., and J.R.F. conceived and designed research; J.B.M., and S.A.B. performed experiments; J.B.M., S.A.B., and J.R.F. analyzed data; J.B.M., S.A.B., J.F., M.S.C., J.P.G., and J.R.F. interpreted results of experiments; J.B.M., S.A.B., and J.R.F. prepared figures; J.B.M., S.A.B., and J.R.F. drafted manuscript; J.B.M., S.A.B., J.F., M.S.C., J.P.G., and J.R.F. edited and revised manuscript; J.B.M., S.A.B., J.F., M.S.C., J.P.G., and J.R.F. approved final version of manuscript.

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