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Visual Search as Effortful Work

Brian A. Anderson and David S. Lee
Department of Psychology, Texas A&M University

Tasks that involve more demanding cognitive operations, such as working memory maintenance and rule switching, tend to be perceived as effortful. People will make choices that minimize the need to perform such tasks and will even accept some measure of physical pain in exchange for the ability to avoid them. Nearly all tasks require that people find and extract relevant perceptual information from their environment, but demands of this nature are often ignored in the study of mental effort. Visual search is sometimes described as "difficult" or "easy" on the basis of search slopes or other performance-based metrics, but how such performance differences map onto conceptions of cognitive demand is unclear. In the present study, we examined whether people would be willing to exert physical effort in exchange for the opportunity to minimize the number of items they needed to search through in a visual search task and whether they would be more willing to endure physical effort demands if it resulted in fewer items needing to be searched. Our results are broadly consistent with the idea that the performance of visual search constitutes effortful work that can trade-off with physical effort demands, which has broad implications for theories of visual information processing and practical considerations for professions that tax peoples' ability to search.

Keywords: selective attention, visual search, mental effort, physical effort, work

When given the option, people generally prefer tasks that minimize physical effort (e.g., Klein-Flügge et al., 2016; Prévost et al., 2010). This preference is thought to reflect an adaptive tendency to conserve energy resources for potential use in the future (Cheval & Boisgontier, 2021; Lieberman, 2015). As a real-world example, when driving to a gym with the intent of exercising, a person might loop the parking lot in search of a close parking space that will minimize the need to walk to and from the gym, engaging in a time-consuming search while passing over a host of open spaces in the more remote region of the lot. Although the entire purpose of the trip is to exert physical effort (in the gym), people's apparent motivation to limit their physical effort immediately before engaging in exercise provides a salient case-in-point for a bias to conserve energy.

This same principle of effort minimization has been applied to the domain of human cognition. When given the option of choosing one of two tasks to perform, participants demonstrate a preference for choosing the task that is less cognitively demanding, which can be operationalized as the task requiring less working memory demand and/or less of a need to switch between task rules (Kool et al., 2010). People are even willing to accept an aversive electric shock in exchange for the ability to avoid performing an epoch of the memory-demanding N-back task, increasingly so with increasing working memory demand (Vogel et al., 2020). It would seem that the tendency to minimize the exertion of effort extends beyond physical effort, encompassing the exertion of mental effort as well. It is also the case that rewards are devalued as a function of the cognitive effort required to obtain them (Apps et al., 2015; Westbrook et al., 2013, 2020), further consistent with a bias to minimize the exertion of such effort.

In naturalistic environments and most laboratory experiment tasks, information gathering is an active process. People need to find and extract relevant perceptual information from their environment while ignoring information that is irrelevant to the task at hand. Do the demands of finding and extracting relevant perceptual information, such as those involved in visual search, meaningfully contribute to the cognitive effort required by a task? Unlike memory-demanding cognitive tasks, people often conduct a visual search with limited awareness of what they have looked at (e.g., Adams & Gaspelin, 2020, 2021; Anderson & Mrkonja, 2021; Chen & Wyble, 2015; Horowitz & Wolfe, 1998; Theeuwes et al., 1998; Võ et al., 2016), maintaining a representation of the searched-for stimulus in active memory (Woodman et al., 2013) and engaging low-demand and potentially largely automatic attentional processes (see Anderson, 2018). Indeed, a number of involuntary, low-demand attentional processes support the selection of pertinent stimuli, which has been argued to reflect an adaptive attentional system that functions to minimize the need for controlled and effortful

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Experiments 4 and 5 were presented at the 2022 annual meeting of the Vision Sciences Society. None of the data and ideas presented were posted on a listserv, shared via a website, or posted to a preprint service.

Brian A. Anderson and David S. Lee jointly developed the study concept and experiment design. Brian A. Anderson coded the experiment and supervised data collection. Brian A. Anderson performed the data analyses. Brian A. Anderson and David S. Lee interpreted the data. Brian A. Anderson drafted the manuscript with input from David S. Lee. All authors approved the final version of the manuscript for submission. Brian A. Anderson and David S. Lee served as lead for writing–original draft.

Correspondence concerning this article should be addressed to Brian A. Anderson, Department of Psychology, Texas A&M University, 4235 TAMU, College Station, Texas 77843-4235, United States. Email: brian.anderson@tamu.edu

processes in the attainment of a desired state (Anderson, 2021). Such findings and theories could be taken to suggest that the attentional demands of searching for and finding a task-relevant stimulus are negligible.

With that said, not all visual search tasks are created equal and it is not uncommon to see a particular visual search task described as "difficult" or "easy" on the basis of the time required to find a target, typically quantified as a function of the number of items in the display that need to be searched through (search slope; Duncan & Humphreys, 1989; Huang & Pashler, 2005; Hulleman, 2010; Wolfe, 2020; Wolfe et al., 1989). Is this a defensible way to characterize visual search? In this context, "difficult" and "easy" are relative terms without any obvious standard upon which to judge something as objectively effortful or demanding. Although it may take a little longer to find a target stimulus under particular task conditions, this need not imply that the task was more cognitively demanding or difficult to complete in any meaningful sense.

In light of these issues, we wondered whether people would perceive a visual search task as effortful, in a manner that maps onto traditional conceptions of task difficulty in the context of visual search. To objectively quantify mental effort, we developed a novel experimental approach in which physical effort and the putative cognitive effort required to find the target of visual search trade-off. Assuming a general bias to conserve energy (Cheval & Boisgontier, 2021; Lieberman, 2015), people should be motivated to exert physical effort in proportion to the cognitive effort they feel that the visual search task requires of them, to some degree balancing the two. In our first three experiments, we sought to test whether the amount of physical effort exerted in our experiment was systematically related to multiple hypothesized indicators of the cognitive demands required of finding a target in a visual search. Importantly, our visual search task had little to no working memory demand (see Woodman et al., 2013) and the searched-for target and stimulus-response mapping remained constant over all trials (in contrast to a task-switching situation), such that task factors with an established link to cognitive demand (e.g., Kool et al., 2010; Vogel et al., 2020; Westbrook et al., 2013) were held constant across visual search displays and were in general minimal.

Experiment 1

In Experiment 1, we had participants perform a visual search task in which they could reduce the burden of visual search by making nontarget items disappear. In order to make items disappear, they needed to exert physical effort, squeezing a hand dynamometer with varying degrees of force. For every 50 ms that the requisite amount of force was continuously applied to the hand dynamometer, a nontarget would be removed from the display. Participants could exert physical effort to remove nontargets both in advance of beginning the search (when item placeholders were presented) and during the act of searching (after the placeholders were removed to reveal the search display). The ability to reduce the search set size before the search commences allows for the measurement of physical effort exertion unconfounded by the amount of time participants spend searching, and when they might be more motivated to exert physical effort to reduce the burden of search (since they otherwise need to wait to begin searching). Of interest was whether participants would perceive visual search as sufficiently mentally effortful that they would exert physical effort in order to offset that burden and whether the amount of effort expended would vary with the difficulty of visual search (operationalized at the group level as search set size and at the individual level as search slope).

Method

Participants

Forty-one participants were recruited from the Texas A&M University community, 35 from whom demographic data was obtained (20 female, 15 male, $M_{age} = 18.8$ years [$SD =$ 0.8 years]). Participants were compensated either with course credit or US$10. All participants were English-speaking and reported normal or corrected-to-normal visual acuity and normal color vision. All procedures were approved by the Texas A&M University Institutional Review Board and were conducted in accordance with the principles expressed in the Declaration of Helsinki. Written informed consent was obtained for each participant. A sample size of $n = 40$ was targeted, and data collection ceased the day that $n = 40$ was reached. Our sample size provided power $(1 - \beta) > 0.8$ with $\alpha = .05$ to detect a main effect of attentional effort as small as $\eta_p^2 = 0.039$ and a main effect of physical effort as small as $\eta_p^2 = 0.019$ assuming a modest correlation among repeated measures of 0.5, as well as a correlation between search slope and effort exertion as small as $r = .421$ (computed using G*Power 3.1).

Apparatus

A Dell OptiPlex 7040 equipped with Matlab software and Psychophysics Toolbox extensions (Brainard, 1997) was used to present the stimuli on a Dell P2717H monitor. Responses were entered using a standard U.S.-layout keyboard. Grip force was applied to a Vernier hand dynamometer (model HD-BTA). The participants viewed the monitor from a distance of approximately 70 cm in a dimly lit room.

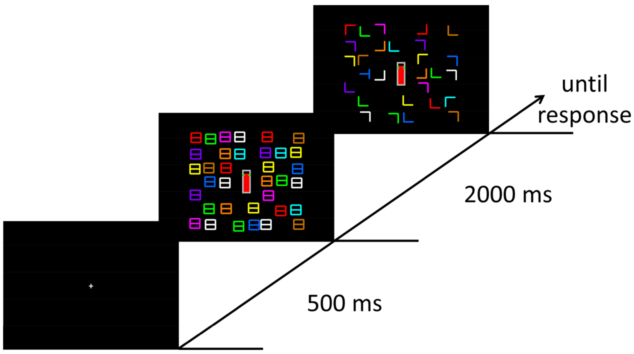
Calibration

Participants squeezed the hand dynamometer as hard as they could using their left hand over three trials to determine their individually calibrated grip strength. Each trial was separated by a 5 s rest period. On each trial, participants saw the text "Ready…" (1 s), "Set…" (1 s), and then "SQUEEZE!!" to signal when to apply force to the hand dynamometer. The word "SQUEEZE!!" remained on the screen for 3 s, and the output from the hand dynamometer was recorded over this entire 3 s duration. The individually calibrated force threshold for each participant was set at the median of nonzero values recorded from the device during the "SQUEEZE!!" epochs over the three trials (combined; see Park et al., 2021).

Stimuli

Each trial consisted of a fixation display, a placeholder display, a search display, and an intertrial interval (ITI). The fixation display consisted of a white plus sign (0.7° × 0.7°) presented at the center of the screen against a black background (see Figure 1). The placeholder display consisted of between 5 and 50 outline squares (each 1.5° × 1.5°) with a line through the middle (having the appearance of a box-shaped figure-eight), along with a force meter with a target fill line indicated. The force meter consisted of a grey outline

Figure 1
Example Trial for Experiment 1



Note. During both the placeholder and search display, a nontarget item would disappear every 50 ms when the force meter was filled above the indicator line. The force meter is filled in proportion to the force applied to a hand dynamometer, with the translation of force to fill calibrated to an individual's measured hand strength. Note that the stimuli are not drawn to scale in this schematic representation of the task. See the online article for the color version of this figure.

rectangle that would fill with red as a force was applied to the hand dynamometer; the target fill line was green. For the search display, segments of remaining placeholders were removed to reveal "L" shaped distractors in four possible orientations (each possible combination of a vertical and horizontal line) and a single sideways "T" that served as the target. A target "T" among "Ls" task was used because it is regarded as a canonically difficult search task producing characteristically large search slopes (Duncan & Humphreys, 1989; Wolfe, 1998, 2020). Each letter/placeholder could appear in one of 50 positions on an 8 × 7 grid with the middle 2 × 3 positions occupied by the force meter (neighboring grid positions were separated by 3.6° in each dimension). The exact position of each letter/placeholder was jittered by up to 0.7° both vertically and horizontally in either direction from the center of its respective grid position. The force meter (2.9° × 9.0°) remained on screen throughout the duration of the search display. The colors of the placeholders and subsequently revealed letter stimuli could be red, green, blue, yellow, white, purple, pink, brown, orange, and cyan. A range of colors was used to increase nontarget heterogeneity, which is known to result in relatively steeper search slopes (Duncan & Humphreys, 1989). The ITI consisted of a blank screen if the correct response to the target was made, whereas the word "Incorrect" was added to the center of the screen if the wrong response had been made in target identification.

Design

The experiment consisted of six blocks of 60 trials each (360 trials total). The number of letters in the search display (and preceding placeholders) varied from five to 50 in increments of five (5, 10, 15, etc.), and the target fill line for the force meter varied across three levels corresponding to an easy, medium, and difficult force requirement (see the "Procedure" section for operationalization of these levels). Each unique combination of set size by force requirement was presented twice in each block, and the order of trials for each block was randomized. The grid position occupied by the target was randomly selected on each trial, as were the positions of the nontargets. Jitter from the center of the grid position was applied randomly to each item by randomly generating the pixel displacement up to the limit described in the preceding section. The color of each letter/placeholder in the search display was randomly selected with the constraint that a color could be used for no more than five letters/placeholders on a given trial. The orientation of the target (top of the "T" on the left or right) was randomly determined on each trial with the constraint that each of the two target orientations was used equally often within each block, and the orientation of the "L" distractors was randomly determined on each trial with the constraint that no one orientation was used more than once more than any other (considering all possible items in the display prior to the removal of any with physical force). When items disappeared from the display with force applied to the hand dynamometer, they disappeared in what amounted to a random order (the reverse of the random order in which the letters/placeholders were assigned to grid positions).

Procedure

Following calibration of the hand dynamometer, participants completed 10 practice trials without the inclusion of the force meter (one for each of the possible display set sizes). Participants then completed one demonstration trial in which they experienced making items disappear from the search display using the hand dynamometer ("grip device"). They were instructed that while the force meter was above the target fill line, items would disappear from the search. For this demonstration, 20 placeholders were presented and the target fill line was set to medium difficulty. Participants needed to make all but one of the placeholders disappear. This demonstration was followed by nine practice trials (using a 3 × 3 combination of physical difficulty [easy, medium, difficult] and set size [10, 25, 50] presented in random order). Participants were explicitly instructed that the grip device could be used to make items disappear both during the placeholder period and after the letters had been revealed, and that they were free to decide when and if they wanted to use the grip device to reduce the number of search items.

The force meter would fill as participants applied force to the hand dynamometer. It was set such that applying force equal to their individually calibrated force threshold would completely fill the meter red, and any amount of force applied below this threshold would proportionally fill the meter red. For the easy, medium, and difficult effort requirement, the target fill line was set at 20%, 50%, and 80% of a participant's calibrated grip strength (these percentages are only intended to reflect approximations of a person's grip strength and do not necessarily reflect maximal voluntary contraction of the hand muscles; they will henceforth be referred to only in the categorical/relative sense of easy, medium, and difficult). For every 50 ms that the force meter was continuously filled above the target fill line, one placeholder/nontarget would disappear from the display (falling below this line would restart the 50 ms counter). Up to every item but the target could be removed using the hand dynamometer, such that it was possible to reduce the search display to only the target.

Each trial began with the fixation display for 500 ms, followed by the placeholder display for 2,000 ms. Immediately after the placeholder display, elements of whatever placeholders remained would disappear to reveal the letters to be searched, constituting the search display. The search display would remain until a response was indicated, and response time (RT) was measured from the onset of the search display (when elements of the placeholders were removed). Participants pressed the "z" key if the top of the sideways "T" was on the left and the "m" key if the top of the sideways "T" was on the right. The ITI (which included "Incorrect" feedback if the wrong key had been pressed) was presented for 1,000 ms. A minimum 60 s break was inserted between each block of trials, with participants needing to manually resume the experiment with a keypress when ready, allowing for the opportunity to rest their hands.

Data Analysis

Our main measure of interest was what we term *set size reduction*, which is the number of search items removed as a result of physical effort. This was computed separately for each combination of set size (5–50) and physical effort demand (easy, medium, and hard), both at the termination of the placeholder display (when the search display was revealed) and the end of the trial (reflecting the grand total set size reduction). Since these two values are not independent, we analyzed each measure of set size reduction using a separate 10 (set size: 5–50 in increments of 5) × 3 (physical effort: easy, medium, and difficult) analysis of variance (ANOVA).

We additionally computed the slope of the RT by set size function for trials on which participants chose not to remove any items when viewing the search display (since on trials for which items are removed during the course of a search, it is difficult to quantify exactly what the functional set size should be given that it cannot be determined whether an item that was removed was already searched prior to its disappearance), which was expressed as ms/item. This measure of search slope served as an indicator of the efficiency of search for a given participant, which was then correlated with the mean set size reduction during the fixed-duration placeholder display to determine whether less efficient searchers were more willing to physically work to reduce their display set size prior to beginning their search. We focused on this measure of set size reduction for correlation analysis since it reflects how hard participants were willing to physically work to make visual search easier uncontaminated by how long it took them to find the target (for someone with a higher search slope, the average search time would be expected to be longer, leaving more time to reduce the set size while the search display was presented).

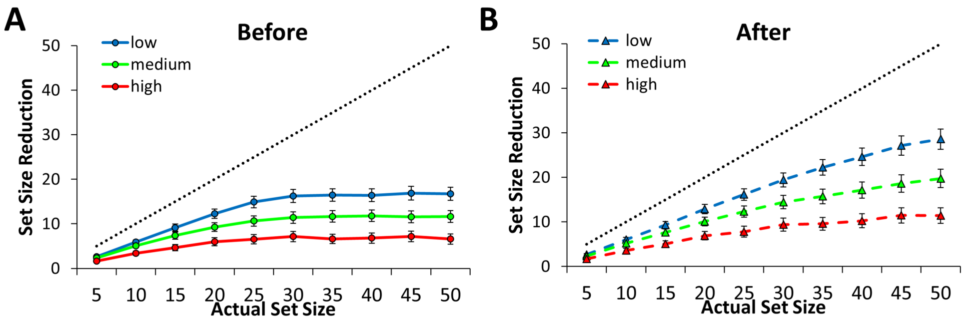
Results

The mean accuracy in the task was 97.7%. As is evident from Figure 2, participants robustly took advantage of the opportunity to exert physical effort in order to reduce the number of items that needed to be searched. At the time of search display onset, a 10 (set size) × 3 (physical effort) ANOVA revealed a significant main effect of physical effort on set size reduction, $F(2, 80) = 68.60$, $p < .001$, $\eta_p^2 = 0.632$, validating our physical effort manipulation (Figure 2A). Participants were less willing to take advantage of the opportunity to exert physical effort to reduce the set size as the amount of physical effort required to do so increased, with mean set size reduction differing significantly between all pairs of conditions, ts > 7.38, ps < .001, d_zs > 1.15. Even at the highest level of physical effort demand, set size reduction was conspicuously above zero. There was also a significant main effect of set size, $F(9, 360) = 76.82$, $p < .001$, $\eta_p^2 = 0.658$, along with a significant physical effort by set size interaction, $F(18, 720) = 37.59$, $p < .001$, $\eta_p^2 = 0.484$. Both of these effects were influenced by the boundary conditions for set size reduction within the fixed 2,000 ms time frame. Mean set size reduction plateaued by about set size 30, likely influenced by the ceiling for the number of items by which the set size could be reduced during the placeholder display. At smaller set sizes, the number of items by which the set size could be reduced was bounded by the actual set size. Even so, the significant interaction coupled with the pattern of data evident from Figure 2A suggests that participants were more sensitive to visual search demands as reflected in set size when physical effort demands were lower, being increasingly willing to exert physical effort as the set size became larger up until the plateau; this was supported by the fact that the interaction was significant when computed over the five smallest set sizes, $F(8, 320) = 37.40$, $p < .001$, $\eta_p^2 = 0.483$, and well accounted for by a linear trend in the interaction term, $F(1, 40) = 71.90$, $p < .001$, $\eta_p^2 = 0.643$, but was nonsignificant when computed over the five largest set sizes, $F(8, 320) = 1.12$, $p = .347$. Overall, mean set size reduction during the placeholder display is consistent with the idea that participants are less willing to exert physical effort to reduce the set size as the physical effort requirements become greater, and on trials on which they commit to exerting physical effort, they generally maintain their grip such that set size reduction becomes bounded by the duration of the placeholder display.

Participants were allowed to exert physical effort for the entire trial, however, allowing for the measurement of effort exertion unbounded by a fixed duration. As is evident from Figure 2, although participants could have ceased exerting physical effort if they were only willing to exert effort while waiting to be able to begin searching, the exertion of physical effort was not limited to the presearch (placeholder) period. In fact, the mean set size reduction increased substantially from what it was at the end of the placeholder period (Figure 2, compare panels A and B). A 10 (set size) × 3 (physical effort) ANOVA performed on total set size reduction by the end of the trial revealed significant main effects of physical effort, $F(2, 80) = 69.34$, $p < .001$, $\eta_p^2 = 0.634$, and set size, $F(9, 360) = 99.10$, $p < .001$, $\eta_p^2 = 0.712$, as well as a significant interaction, $F(18, 720) = 50.72$, $p < .001$, $\eta_p^2 = 0.559$ (Figure 2B). The main effect of physical effort maintains the influence observed during the placeholder display. Pairwise comparisons across different set sizes revealed significant differences across every possible pair of set sizes, $t(40) = 2.17$, $p = .036$, $d_z = 0.34$ for 45 versus 50, other ts > 4.50, ps < .001, d_zs > 0.70, making it clear that the main effect of set size was not simply the product of a floor effect at smaller set sizes. The larger the set size, the more willing participants were to exert physical effort in order to reduce the number of items they needed to search through. We reiterate that the measures of set size reduction taken after the placeholder display ("before" search commences) and at the conclusion of the trial ("after") are not independent, which is why they were analyzed separately. The substantial differences between the two are influenced by the fact that the duration of the placeholder display is fixed, which creates a ceiling effect on the number of items that can be removed from the display during that period.

Another way to plot set size reduction is as a proportion of the total set size. Plotting the set size reduction as a proportion

Figure 2
Behavioral Data for Experiment 1

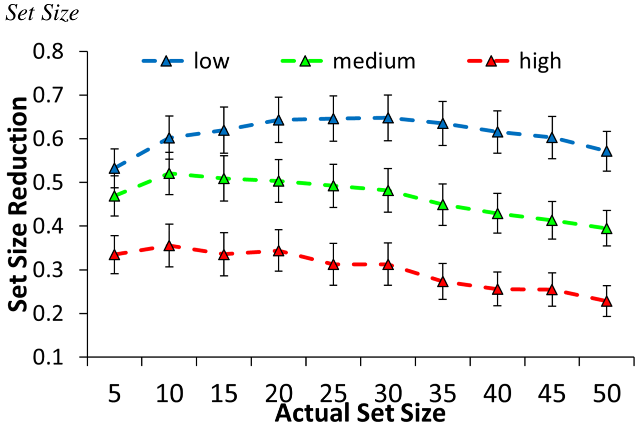


Note. Relationship between actual set size at the onset of the trial (*x*-axis) and the mean number of items that participants removed from the display with physical force (set size reduction, *y*-axis) as a function of the physical force required to remove items (low, medium, and high) and whether the measurement was taken before (immediately following the fixed-duration placeholder display, when the search display was revealed, panel A) or after search (at the conclusion of the trial, once the target had been reported, panel B). The black dotted line indicates the maximum possible number of items that could have been removed (number of nontargets or actual set size minus one). Error bars reflect the standard error of the mean (SEM). See the online article for the color version of this figure.

(Figure 3) suggests that, for trials with low physical effort demand, participants tended to work to remove approximately 60% of the display items consistently across set sizes. When physical effort demands were medium and high, however, the proportion of display items removed tended to decline over the set size. That is, as physical demands became more difficult, participants moved from removing a consistent proportion of the display items (low physical demand condition, Figure 3) toward removing a consistent number of items regardless of set size (high physical demand condition, Figure 2).

The mean search slope was 40 ms/item, consistent with inefficient search, with a range of 14–72 ms/item across participants. There were also substantial individual differences across participants with respect to the degree to which they used the grip device to reduce the search set size. Consistent with the idea that individuals for whom search is more difficult would be more willing to exert physical effort in order to reduce the demands of visual search, there was a significant correlation between set size reduction during the placeholder display and individual search slope, $r = .461$, $p = .002$ (Figure 4). It was also the case that set size reduction, computed both during the placeholder display and at the conclusion of the trial, was correlated with mean RT, $rs < -.704$, $ps < .001$, such that exerting physical effort reduced the total time spent searching.

Figure 3
Mean Set Size Reduction for Experiment 1 (y*-axis) After the Search Had Been Completed as a Function of the Actual Set Size at Trial Onset (*x*-axis) and the Physical Force Required to Remove Items (Low, Medium, and High), Expressed as a Proportion of Actual Set Size*



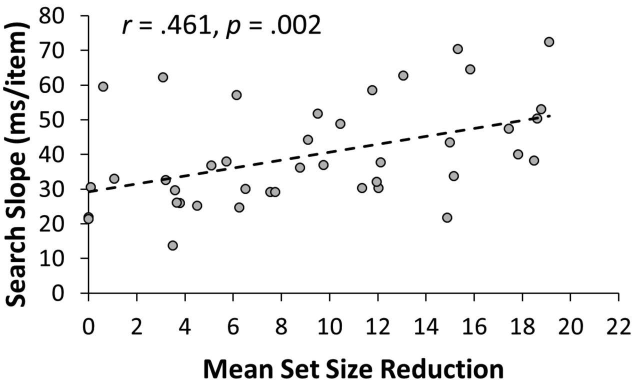
Note. Error bars reflect the standard error of the mean (SEM). See the online article for the color version of this figure.

Discussion

Participants were willing to exert physical effort when such effort reduced the search set size by causing nontargets to disappear. The less force that was required to influence search, the more willing participants were to engage in this opportunity, validating the physical effort manipulation. Even after the search display had been revealed from the placeholders, participants continued to exert physical effort to reduce their search set size. Importantly, participants exerted physical effort as a function of set size, physically working harder to reduce the set size when more items needed to be searched through, especially when the physical effort demands of doing so were low.

Interestingly, when physical effort demands were low (easy), participants tended to reduce the search display by a consistent proportion of items, whereas when physical effort demands were high (difficult), set size reduction moved toward a consistent number of items regardless of set size. We do not see evidence that participants have a desired set size that they target in expending physical effort. It seems instead that when physical demands are low, the physical effort they choose to exert scales with set size, but when physical demands are high, participants tend to reach their ceiling for willingness to exert physical effort and become far less sensitive to set size. Across all levels of physical effort demand, however, including the highest level of effort tested (80% of calibrated maximal force), participants exhibit a robust willingness to work in order to reduce the search set size by at least some degree.

Figure 4
Correlation Between Mean Set Size Reduction During the Course of the Placeholder Display (Across All Trials, x-axis*) and Individual Search Slope (* y-axis*) for Experiment 1*



Across participants, individual search slopes computed on trials where no items were removed during the search portion predicted willingness to exert physical effort prior to the revealing of the search display. That is, the more "difficult" search was for a participant as measured via search slope, a canonical measure of search difficulty (see, e.g., Duncan & Humphreys, 1989; Huang & Pashler, 2005; Hulleman, 2010; Wolfe, 2020; Wolfe et al., 1989), the harder the participant was willing to work to reduce the number of items that needed to be searched through. Coupled with the main effect of set size and interaction between set size and physical effort demands with respect to set size reduction, we find converging evidence that as putative search demands increased, participants became increasingly willing to exert physical effort in order to reduce the number of items they needed to search through.

Experiment 2

In Experiment 1, search difficulty was manipulated via set size and quantified on both the group (as a function of set size itself) and individual (as a function of search slope) level, which was in each case related to the amount of physical effort participants chose to exert in order to remove items from the search. Physical effort requirements varied across trials, while the visual search task was held constant apart from set size. Experiment 2 sought a more direct manipulation of visual search effort that was not itself contingent on set size, varying the search task across trials while requiring a consistent amount of physical effort to reduce set size. To this end, we varied the heterogeneity of nontargets, which is known to robustly influence search slope or "difficulty" (e.g., Duncan & Humphreys, 1989). In some trials, the nontargets were homogeneous, while other trials mirrored the high degree of nontarget heterogeneity used in Experiment 1. The color of the placeholders provided advance information about the heterogeneity of the upcoming visual search display, such that participants could choose how hard to work physically in anticipation of the upcoming search difficulty.

Method

Participants

Thirty-four new participants were recruited from the Texas A&M University community using the same compensation and inclusion criteria, 33 from whom demographic data was obtained (19 female, 13 male, 1 gender not reported; $M_{age} = 19.3$ years [$SD = 1.3$ years]). All procedures were approved by the Texas A&M University Institutional Review Board and were conducted in accordance with the principles expressed in the Declaration of Helsinki. Written informed consent was obtained for each participant. Our sample size provided power $(1 - \beta) > 0.9$ with $\alpha = .05$ to replicate the main effect of the set size of the magnitude observed in Experiment 1, as well as power $(1 - \beta) > 0.8$ to replicate the correlation between set size reduction and search slope (computed using G*Power 3.1).

Apparatus and Calibration

Identical to Experiment 1.

Stimuli

Identical to Experiment 1 with the exception that for half of the trials, all of the placeholders were white and, when the search display was revealed, all of the nontargets were "Os." This display of homogeneous nontargets was referred to as the *easy search display*, which could be contrasted with the *difficult search displays* that maintained the same heterogeneous array of nontargets used in Experiment 1.

Design

As with Experiment 1, the experiment consisted of six blocks of 60 trials each (360 trials total). This time, however, the target fill line for the force meter was set at the medium difficulty level across all trials. The number of letters in the search display (and preceding placeholders) again varied from 5 to 50 in increments of five. Each unique combination of set size by search difficulty (easy/homogeneous and difficult/heterogeneous) was presented three times in each block. The design was otherwise identical to Experiment 1.

Procedure

The procedure was the same as Experiment 1 with the exception that the target fill line for the force meter was held constant across trials at the medium difficulty level (i.e., 50% of individually calibrated grip strength). In the task instructions, it was explicitly indicated that the color of the placeholders also predicted whether the nontargets would be "Ls" or "Os." The second set of practice trials consisted of 10 trials, five of the difficult search and five of the easy search (each with set sizes 10, 20, 30, 40, and 50).

Data Analysis

The analytic approach mirrored that of Experiment 1, replacing the factor of physical effort with search difficulty (easy, hard). Search slope was computed separately for the easy and difficult visual search displays and each correlated with mean set size reduction computed specifically over the respective display type. We also directly compared the search slope between the two display types via a paired samples *t*-test to verify that the putatively easier search displays indeed yielded shallower search slopes. Note that for one participant, the search slope could not be computed for difficult visual search trials, as this participant reduced the set size to some degree on every such trial during the search display for which the set size was not already reduced to one item from the placeholder display, resulting in an infinite number of possible search slopes.

Results

The mean accuracy in the task was 98.7%. Confirming the manipulation of search difficulty, the search slope for easy visual search (homogeneous nontargets) was significantly and substantially shallower than the search slope for difficult visual search (heterogeneous nontargets), $t(32) = 11.95$, $p < .001$, $d_z = 2.08$ (Figure 5A). In each case, however, the search slope was robustly above zero, ts > 8.41, ps $< .001$, d_zs > 1.44, with the random arrangement of items across the display likely precluding purely pop-out search in the case of homogeneous nontargets. Consistent with Experiment 1, the search slope for both easy search, $r = .807$, $p < .001$ (Figure 5B), and difficult search, $r = .407$, $p = .019$ (Figure 5C), was significantly correlated with set size reduction for the respective display type during the placeholder period. Thus, even for an easy visual search in which the search slope was overall shallow, participants for whom the search was comparatively more difficult (or, said another way, less easy) were more willing to exert physical effort to reduce their search set size before the search commenced. Also consistent with Experiment 1, set size reduction (at each time point) was negatively correlated with mean RT, marginally in the case of set size reduction computed on easy visual search trials rs $< -.331$, ps $< .056$, and robustly in the case of set size reduction computed on difficult visual search trials, rs $< -.660$, ps $< .001$.

With respect to the placeholder display, there were main effects of set size, $F(9, 297) = 37.65$, $p < .001$, $\eta_p^2 = 0.533$, and search difficulty on set size reduction, $F(1, 33) = 20.09$, $p < .001$, $\eta_p^2 = 0.378$, in addition to a significant interaction between these two factors, $F(9, 297) = 12.58$, $p < .001$, $\eta_p^2 = 0.276$ (see Figure 6A). Set size reduction increased more strongly with display set size for difficult compared to easy search trials before plateauing at larger set sizes. This overall pattern was supported by a significant interaction between set size and search difficulty when computed over the five smallest set sizes, $F(4, 132) = 8.43$, $p < .001$, $\eta_p^2 = 0.204$, which was well accounted for by a linear trend in the interaction term, $F(1, 33) = 10.90$, $p = .002$, $\eta_p^2 = 0.248$, while the interaction was nonsignificant when computed over the five largest set sizes, $F(4, 132) = 1.07$, $p = .373$.

At the end of the trial, total set size reduction revealed a similar pattern, which like Experiment 2 did not exhibit the plateau at larger set sizes. There was again a significant main effect of the set size, $F(9, 297) = 52.62$, $p < .001$, $\eta_p^2 = 0.615$, and search difficulty, $F(1, 33) = 29.99$, $p < .001$, $\eta_p^2 = 0.476$, along with a significant interaction, $F(9, 297) = 26.74$, $p < .001$, $\eta_p^2 = 0.448$ (see Figure 6B). All pairwise comparisons across the set size were significant, ts > 2.75, ps $< .01$, d_zs > 0.47, with the exception of 45 versus 50, $t(33) = 1.27$, $p = .211$.

Discussion

We observed the expected robust influence of display heterogeneity on the search slope, confirming the manipulation of search difficulty. Importantly, on difficult search trials, both before and during a search, participants exerted more physical effort to reduce the set size. For both easy and difficult searches, individual search slopes again predicted willingness to work prior to search display onset. On both the group and individual levels, the more difficult the visual search, the more physical effort participants exerted in order to reduce the search set size.

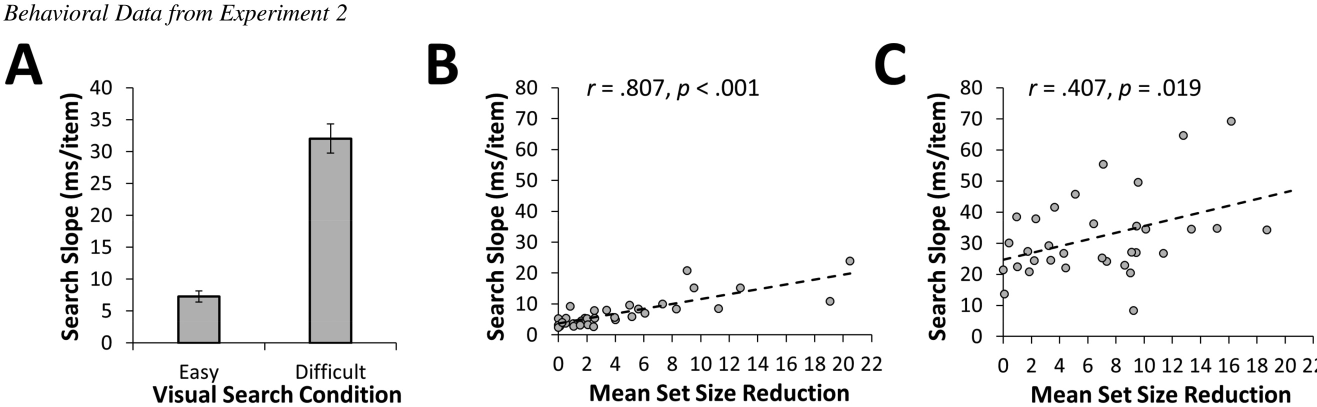
Experiment 3

In both Experiments 1 and 2, the exertion of physical effort would reduce the search set size. This had the function of reducing search difficulty, but it also had the function of reducing the total duration of the experiment. Although the amount of energy expended and the amount of time spent exerting effort are intrinsically correlated, participants may have exerted physical effort simply to finish the experiment faster and would have exerted such effort regardless of the specific nature of the task.

This explanation seems unlikely to provide a complete account of our data. Participants were clearly sensitive to both search difficulty and physical effort demands during the placeholder period, when they otherwise wait for a fixed amount of time for the search display

Figure 5

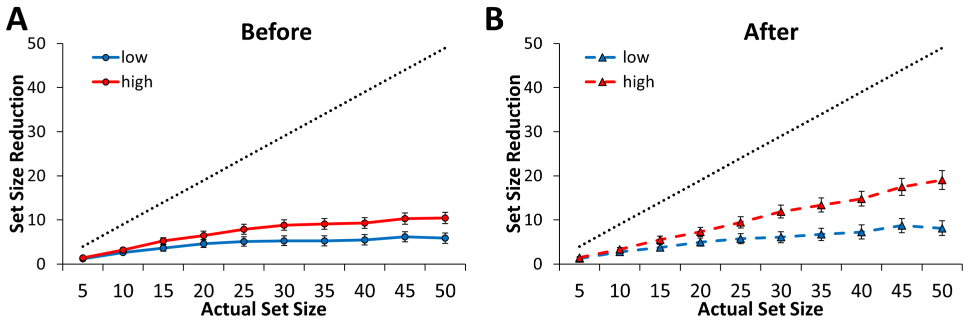
Behavioral Data from Experiment 2



Note. (A) Comparison of mean search slope as a function of search difficulty. Correlation between mean set size reduction during the course of the placeholder display (*x*-axis) and individual search slope (*y*-axis), separately for easy (B) and difficult search trials (C). Error bars reflect the standard error of the mean (SEM).

Figure 6

The Relationship Between the Actual Set Size at the Onset of the Trial (x*-axis) and the Mean Number of Items That Participants Removed from the Display with Physical Force (Set Size Reduction,* y*-axis) for Experiment 2 as a Function of the Difficulty of the Visual Search Task Given the Nontarget Heterogeneity (Low and High) and Whether the Measurement was Taken Before (Immediately Following the Fixed-Duration Placeholder Display, When the Search Display was Revealed, Panel A) or After Search (At the Conclusion of the Trial, Once the Target Had Been Reported, Panel B)*



Note. The black dotted line indicates the maximum possible number of items that could have been removed (number of nontargets or actual set size minus one). Error bars reflect the standard error of the mean (SEM). See the online article for the color version of this figure.

to be revealed. During this epoch, any physical effort exerted would be expected to speed overall performance, yet participants did not indiscriminately exert effort during this period. Participants were instead quite discerning with when and how much physical effort they expended, suggesting that physical effort was calibrated to manage search difficulty and not solely the product of a strategy to minimize the duration of the experiment independently of search demands.

With that said, exerting physical effort did serve to shorten the duration of Experiments 1 and 2, as attested to by the correlation between set size reduction and mean RT. A more compelling demonstration of the role of visual search demands *per se* influencing willingness to exert physical effort would come from an experiment in which there was absolutely no effect of physical effort on shortening the duration of a trial (and by extension the total duration of the experiment). To this end, in Experiment 3, the time between successive trials was fixed and participants were explicitly informed of this. One trial would occur every 9 s regardless of how quickly the target was reported, which was accomplished by varying the ITI to achieve a desired trial duration. To ensure a lack of ambiguity with respect to the relationship between physical effort and trial duration, we adopted a strong manipulation in which participants were explicitly informed of the fact that one trial would be presented every 9 s and there was nothing they could do to make the experiment go faster or slower. If participants are willing to exert any physical effort at all under such conditions, it must be because they wish to reduce the difficulty of visual search in a manner that is not reducible to a strategy to complete the experiment faster.

Method

Participants

Twenty-six new participants were recruited from the Texas A&M University community using the same compensation and inclusion criteria, 25 from whom demographic data was obtained (12 female, 13 male, $M_{\text{age}} = 19.3$ years [$SD = 1.1$ years]). All procedures were approved by the Texas A&M University Institutional Review Board and were conducted in accordance with the principles expressed in the Declaration of Helsinki. Written informed consent was obtained for each participant. Our sample size provided power $(1 - \beta) > 0.9$ with $\alpha = .05$ to replicate the main effect of physical effort and set the size of one-fourth of the magnitude observed in Experiment 1 (computed using G*Power 3.1). Given the specific research question, we did not power Experiment 3 to replicate the correlation between search slope and set size reduction, which with the present sample size was 0.68.

Apparatus and Calibration

Identical to Experiment 1.

Stimuli, Design, and Procedure

Identical to Experiment 1 with the exception that the ITI was adjusted such that a trial began every 9 s and participants completed only four blocks of trials (since each block now took longer to complete). The search display would time out after 5 s, in which case participants would receive the feedback "Too Slow." Based on how long the search took to complete, the duration of the ITI was adjusted to accomplish a total trial duration of 9 s; 5 s was selected for the timeout limit because only 1.5% of responses fell above this threshold without a timeout limit in Experiment 1, so this would provide little time pressure while maximizing the speed with which trials could be presented at a fixed pace. Participants were explicitly informed that one trial would be presented every 9 s and that, although they could use the grip device to reduce the number of items they needed to search through, using the grip device could not change how long it would take to complete the experiment.

Data Analysis

The analytic approach mirrored that of Experiment 1. Although the experiment was not powered to replicate a correlation between search slope and set size reduction, we still report the correlation for completeness. For the sake of computing accuracy, timeouts were scored as errors.

Results

The mean accuracy in the task was 98.1%. With respect to set size reduction during the placeholder display, we replicated the main effect of set size, $F(9, 225) = 55.09$, $p < .001$, $\eta_p^2 = 0.688$, the main effect of physical effort, $F(2, 50) = 53.64$, $p < .001$, $\eta_p^2 = 0.682$, and the interaction, $F(18, 450) = 18.75$, $p < .001$, $\eta_p^2 = 0.429$, with the characteristic plateau at larger set sizes (Figure 7A). At the end of the trial, the main effects of the set size, $F(9, 225) = 85.62$, $p < .001$, $\eta_p^2 = 0.774$, and physical effort, $F(2, 50) = 47.22$, $p < .001$, $\eta_p^2 = 0.654$, were still evident, as was the interaction, $F(18, 450) = 21.62$, $p < .001$, $\eta_p^2 = 0.464$ (Figure 7B). Pairwise comparisons revealed significant differences between all combinations of physical effort, ts > 6.24, ps < .001, d_zs > 1.22, and all combinations of set size, ts > 3.57, ps < .002, d_zs > 0.70.

The correlation between search slope and mean set size reduction was replicated, $r = .478$, $p = .013$, despite the fact that this particular analysis was underpowered. As in Experiment 1, set size reduction both during the placeholder display and by the end of the trial were negatively correlated with mean RT, rs < −.513, ps < .002. Mean set size reduction across all trials was not significantly greater in Experiment 1 ($M = 12.3$, $SD = 7.34$) compared to Experiment 3 ($M = 13.6$, $SD = 7.33$), $t(65) = 0.69$, $p = .494$; if anything, the difference was numerically in the opposite direction, providing no evidence that the inability to influence the duration of the experiment reduced willingness to physically work.

Discussion

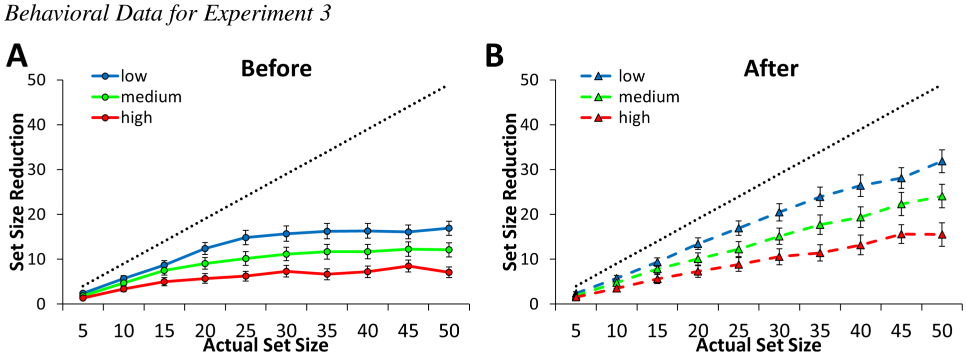
Participants still exerted physical effort in order to reduce their search set size. The main effect of physical effort and the main effect of set size on set size reduction was replicated. This was despite the fact that the rate with which trials were presented was fixed such that finding the target more quickly would result in no net difference in the time that the experiment would take to complete, which participants were explicitly informed of.

We found no evidence that set size reduction was smaller in Experiment 3 compared to Experiment 1, and if anything the trend was in the opposite direction. This is striking, as we implemented a strong manipulation in the present experiment in which participants were explicitly instructed that nothing they could do with respect to physical effort could make the experiment go faster, which may have functioned to disincentivize the use of the grip device by framing its use pessimistically. We also reiterate that the effort involved in visual search and the total time spent searching are intrinsically correlated—the present experiment was presumably less mentally effortful than Experiment 1 because there were fewer overall visual search trials that needed to be completed.

In light of the aforementioned considerations, why was set size reduction not at least somewhat reduced compared to Experiment 1? Would the reduced accumulation of attentional effort from fewer total trials not predict a significant reduction in the willingness to offset attentional effort with physical effort? In this context, we note that the increased ITI in Experiment 3 provided more time between trials for the participant's hand to recover from physical exertion, and we speculate that this increased recovery time may have increased the motivation to use some of the recovered strength to reduce the set size, offsetting any reduction in attentional effort brought about by fewer total trials. Importantly, however, if the minimization of experiment duration was responsible for the results of Experiments 1 and 2, increased time to physically recover between trials should have been of no consequence in Experiment 3, since participants would have nothing to physically recover from had

Figure 7

Behavioral Data for Experiment 3



Note. Relationship between actual set size at the onset of the trial (x-axis) and the mean number of items that participants removed from the display with physical force (set size reduction, y-axis) as a function of the physical force required to remove items (low, medium, and high) and whether the measurement was taken before (immediately following the fixed-duration placeholder display, when the search display was revealed, panel A) or after search (at the conclusion of the trial, once the target had been reported, panel B). The black dotted line indicates the maximum possible number of items that could have been removed (number of nontargets or actual set size minus one). Error bars reflect the standard error of the mean (SEM). See the online article for the color version of this figure.

they not used the grip device for the sole sake of easing the burden of visual search.

It is clear from the results of Experiment 3 that a motivation to complete the experiment more quickly cannot solely account for participants' willingness to exert physical effort in our task. Participants robustly exert physical effort for the sole sake of reducing the demands of performing visual search per se, even when they know this will not impact the total duration of the experiment. This is not to imply that a desire to exert physical effort in order to minimize the average time needed to find the target (and thus the total duration of the experiment) played no role in Experiments 1 and 2, only that a strategy predicated on this desire cannot provide a complete account of our data.

Experiment 4

Experiments 1–3 assess how much physical effort participants choose to exert in order to make the visual search easier. In Experiment 4, we test the reverse, namely how much attentional effort participants are willing to exert in the context of visual search in order to make a task of physical effort easier. In order to provide such as test, a paradigm that affords participants a choice of how hard to search is needed. To this end, we adapted the Adaptive Choice Visual Search (ACVS) task in which participants are presented with stimuli in two task-relevant colors and can choose to find a target of either color, with one target in each of the two task-relevant colors present on each trial (Hansen et al., 2019; Irons & Leber, 2016, 2018; Kim et al., 2021; Lee et al., 2022). Importantly, in our adapted version, reporting a target rendered in one of the two colors tended to result in a high physical effort demand, while reporting a target rendered in the other color tended to result in a low physical effort demand. The ratio of stimuli in one task-relevant color compared to the other also varied, such that there was always a color that had a smaller set size to search through. Participants were provided no information about any of these aspects of the task and were simply instructed to search for whichever target they wanted to on each trial. Of interest was whether participants would come to prefer searching for the color of the smaller set size and also the color associated with lesser physical effort requirements, which would be reflected in the main effect of attentional effort (set size) and physical effort demands on the probability of reporting a target rendered in the color of which there were fewer stimuli in the display to search through.

Method

Participants

Thirty participants (15 female, 15 male; $M_{\text{age}} = 19.2$ years, [$SD = 2.4$ years]) were recruited from the Texas A&M University community, using the same compensation and inclusion criteria. All procedures were approved by the Texas A&M University Institutional Review Board and were conducted in accordance with the principles expressed in the Declaration of Helsinki. Written informed consent was obtained for each participant. Our sample size provided power $(1-\beta) > 0.8$ with $\alpha = .05$ to detect a main effect of attentional effort as small as $\eta_p^2 = 0.053$ and a main effect of physical effort as small as $\eta_p^2 = 0.065$, each of which was considerably smaller than the effects observed in Experiments 1–3, again assuming a modest correlation among repeated measures of 0.5 (computed using G*Power 3.1).

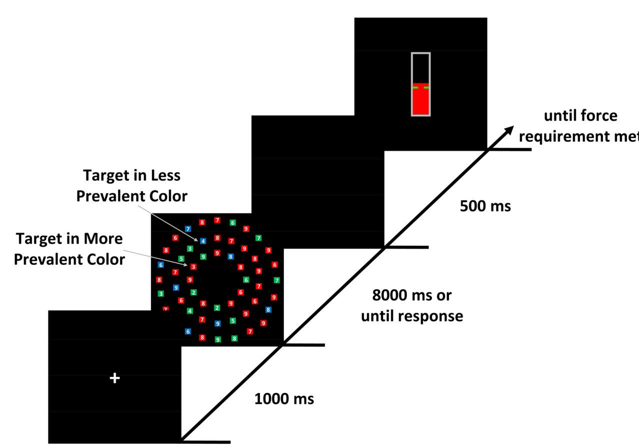
Apparatus and Calibration

Identical to Experiment 1.

Stimuli

Each trial consisted of a fixation display, the visual search array, an interstimulus interval (ISI), the presentation of a force meter, and an ITI (see Figure 8). The fixation display consisted of a white plus sign presented at the center of the screen against a black background. The visual search display was composed of 54 colored squares (each approximately 1.1° × 1.1° visual angle) arranged in three concentric rings around the center of the screen. The inner (radius 7.3°), middle (radius 10.1°), and outer rings (radius 13.0°) were composed of 12, 18, and 24 squares, respectively, positioned equidistant from each other. Each search trial contained red, blue, and green squares. Each square contained a digit between 2 and 9, subtending 0.4° × 0.4°. There was one blue and one red target on each trial, containing a digit 2–5, while red and blue nontargets contained a digit 6–9; green squares could contain any digit 2–9. If no response was recorded within the given time limit, a feedback display was inserted immediately following the search array, which consisted of the words "Too Slow" presented at the center of the screen; if a response was given that did not correspond to a target digit on that trial, the feedback instead displayed the words "Invalid Response." The ISI and ITI consisted of a blank screen, and the force meter consisted of a grey-outlined bar that filled with color in proportion to the force applied to the hand dynamometer, with a broken green line indicating the target fill/force for that trial.

Figure 8
Example Trial for Experiment 4



Note. The color fill for the force meter matched the color of the reported target, one of which was associated with high physical effort demand and the other with low physical effort demand. This trial depicts a more difficult effort demand, with the indicator line reflecting a target force of 42.5% of the maximum which needed to be maintained for 3 s to progress to the next display. Stimuli are not drawn to scale. See the online article for the color version of this figure.

Design

The experiment consisted of 4 blocks of 60 trials each (240 trials total). Within each block, there were 10 trials with 3 red and 37 blue squares, 10 trials with 8 red and 32 blue squares, 10 trials with 13 red and 27 blue squares, 10 trials with 3 blue and 37 red squares, 10 trials with 8 blue and 32 red squares, and 10 trials with 13 blue and 27 red squares. On every trial, the remaining 14 squares were green. The position of the red and blue targets was randomly determined on each trial, as were the digits within the boxes, using the ranges outlined in the "Stimuli" section (i.e., 2–5 for red and blue targets, 6–9 for red and blue nontargets, and 2–9 for green boxes) with the constraint that the red and blue target could not contain the same digit on a given trial (such that which target digit a participant reported was diagnostic of which color target they found). Green squares were allowed to contain a digit 2–5 to prevent the identity of a digit alone from being diagnostic of target status, requiring the processing of stimulus color in order to perform the task accurately. The order of trials was randomized, as was the assignment of colors to individual squares on each trial in accordance with the overall color distribution designated for that trial (e.g., 3 red and 37 blue).

Procedure

Following calibration of the force threshold for the hand dynamometer, the visual search task began with 8 untimed practice trials without the force requirement following each trial. Participants were instructed to press the "v," "b," "n," and "m," keys on the keyboard using their right index, middle, ring, and pinky fingers which mapped onto target digits 2–5, respectively. They were informed that two targets were present on each trial, one in red and one in blue and that they only needed to report one of those two targets on any single trial. Participants then practiced 12 trials with the timeout limited added, which was 8 s. Finally, they completed 12 full practice trials with the force requirement included, although during these practice trials, the force meter always filled with white and the force required to progress to the next trial was randomly determined. Participants were instructed that on some trials the force required would be "easy," with the green marker line being low and only needing to keep the force meter above that line for "a split second" (in actuality, 200 ms), while on other trials the force required would be "more difficult," with the green marker line being higher and needing to keep the force meter above the line for "3 straight seconds." This line reflected 10% and 42.5% of the calibrated force threshold, respectively. For the more difficult force requirement, the meter was in actuality allowed to fall as low as 40% without restarting the 3 s requirement (providing a small grace window). Participants were not given any information about any relationship between target color and force requirements.

On each trial, the fixation display lasted for 1,000 ms, and the visual search array for 8,000 ms or until a response was recorded. Performance feedback, in the event of an incorrect response or a timeout, lasted for 1,000 ms. The ISI was 500 ms and the ITI was 1,000 ms; the force meter remained on the screen until the force requirement had been met. As in Experiments 1–3, the bar filled with color in direct proportion to the amount of force applied such that 100% (or more) of the calibrated force would fill the bar completely. The fill color matched the color of the reported target in the event of a correct response, and was white in the event of an incorrect response or a timeout; participants were not explicitly informed of the link between their choice of target and the fill color of the force meter.

For one of the two target colors, if a target was reported in this color, there was an 80% chance that the grip task would be difficult and a 20% chance that the grip task would be easy. This will be referred to as the *physically demanding color*. For the other color target, these contingencies were reversed, making reporting a target in this color less demanding of physical effort. Which color served as the physically demanding color was counterbalanced across participants. This made is such that the physically demanding color was consistent across trials, but which color had fewer items to search through varied, such that it was sometimes easier to search for the color target associated with greater physical effort demand (to varying degrees based on the ratio of red-to-blue items). At the end of the task, participants answered a question probing the strategies that they had used to search through the displays.

Strategy Assessment

Upon completion of the visual search task, participants were asked to indicate which of the following statements described how they performed the task. They were asked to select as many of the statements as were true for them. The statements were presented in the same order to all participants.

(1) I tended to look for a red target because red targets were generally easier to find.
(2) I tended to look for blue targets because blue targets were generally easier to find.
(3) I tended to look through whichever target color there were fewer boxes of.
(4) I tended to look for numbers 2–5 and then check to make sure a number I found was not green.
(5) I tended to look for blue targets because I often had to squeeze less hard after finding a blue target.
(6) I tended to look for red targets because I often had to squeeze less hard after finding a red target.
(7) I tended to search without really thinking about how I was searching.

Data Analysis

Which color target participants found was coded with respect to whether it was the less prevalent color, which was broken down by the distribution of red-to-blue stimuli (attentional demand) and the physical effort associated with the less prevalent color (physical demand). RT was measured from the onset of the visual search array.

Results

Overall accuracy in the task was 96.5%, indicating that participants generally reported a valid target within the time limit provided.

A 3 × 2 ANOVA on the proportion of attentionally less demanding targets identified (i.e., proportion of targets reported in the less prevalent color) revealed a main effect of attentional demand, $F(2, 58) = 45.19$, $p < .001$, $\eta_p^2 = 0.609$, and a main effect of physical demand, $F(1, 29) = 8.16$, $p = .008$, $\eta_p^2 = 0.220$. The interaction between attentional and physical demand was not significant,

$F(2, 58) = 0.99$, $p = .376$, with the two effort requirements producing additive effects on choice behavior (Figure 9A). That is, the fewer stimuli of a particular color were present on a given trial, the more likely participants were to report a target of that color, while at the same time, participants were in general less likely to report a target rendered in the physically demanding color.

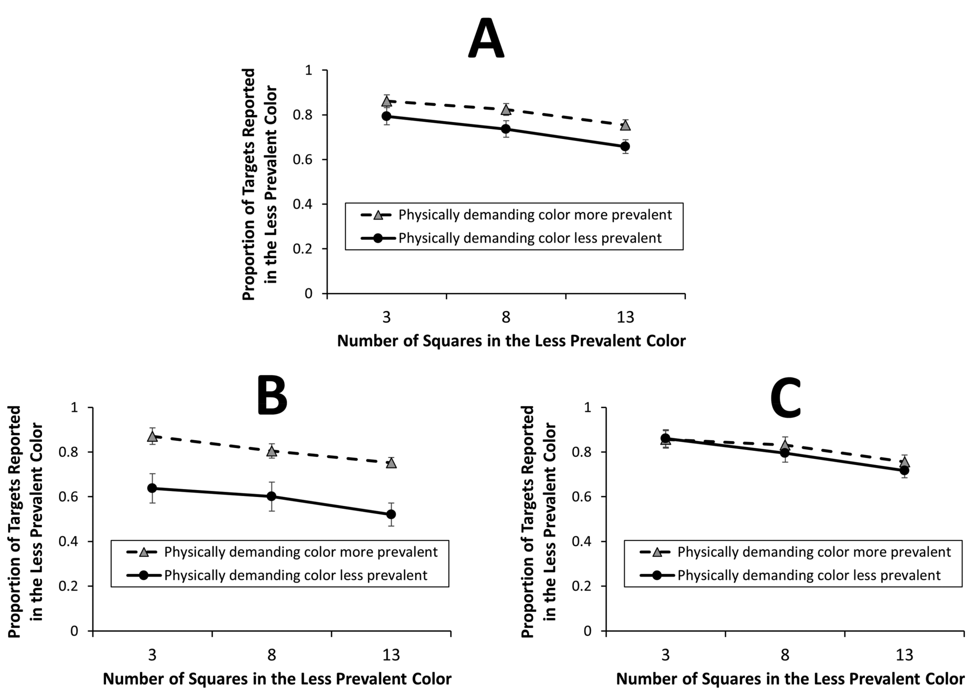
Concerning strategy, zero participants indicated contradictory strategies (e.g., preferentially searching for both red and blue targets because they thought that each was easier to find) and zero participants indicated a strategy that conflicted with the task contingencies (e.g., searching for blue targets because they tended to result in less of a physical effort requirement when in fact blue targets were associated with the need for greater physical effort). Nineteen participants reported using a strategy in which they intentionally searched through the less prevalent color. However, only nine participants endorsed a strategy of searching for a color because it tended to result in them having to work less hard physically. Five participants endorsed a strategy of simply preferring to search through a particular color in general (for three it was the physically less demanding color and for two it was the more physically demanding color), seven participants indicated searching first for low digits irrespective of color, five participants indicated searching without thinking about how they were searching at least some of the time, and one participant did not endorse any of the strategy choices. Note that participants could endorse any of the strategy options and several endorsed more than one.

Conscious use of a strategy based on physical effort demands robustly interacted with the influence of physical demand on choice behavior when entered into the same ANOVA as a between-subjects factor, $F(1, 28) = 14.03$, $p = .001$, $\eta_p^2 = 0.609$. For the nine participants who reported using this strategy, the main effect of physical demand was substantial, $F(1, 8) = 24.26$, $p = .001$, $\eta_p^2 = 0.752$ (Figure 9B), while for the 21 participants who did not report using this strategy, the effect of physical demand was nonsignificant, $F(1, 20) = 0.69$, $p = .416$ (Figure 9C). Even for just the participants who reported prioritizing the color associated with less physical demand, there was still a main effect of attentional demand on trials in which the more physically demanding color was the less prevalent color, $F(2, 16) = 7.63$, $p = .005$, $\eta_p^2 = 0.488$, suggesting that they were more willing to endure the higher physical effort demand when finding and reporting a target rendered in the associated color was less attentionally demanding.

In contrast to the influence of physical demand, conscious use of a strategy based on attentional demand did not interact with the influence of attentional demand on choice behavior, $F(2, 56) = 0.94$, $p = .398$. Participants who both did and did not report conscious use of this strategy showed a robust effect of attentional demand on performance, Fs > 8.29, ps $< .003$.

To verify our manipulation of attentional demand, we examined RT as a function of the number of squares presented in the less prevalent color (regardless of what color target participants actually chose). As expected, a robust main effect was observed in which

Figure 9
Choice Data for Experiment 4



Note. (A) The proportion of targets reported in the less prevalent (i.e., attentionally less demanding) color, as a function of attentional demand (specific number of squares in the less prevalent color, *x*-axis) and the physical demand associated with the less prevalent color. The same data are separated for participants who did (B, $n = 9$) and did not (C, $n = 21$) report conscious use of a strategy based on physical effort demands. Error bars reflect the standard error of the mean (SEM).

the search was faster the fewer the squares presented in the less prevalent color, $F(2, 58) = 142.70$, $p < .001$, $\eta_p^2 = 0.831$, with significant differences observed between each level of the manipulation, ts > 9.80, ps < .001, d_zs > 1.78 (Figure 10A). Second, for the participants who reported consciously using a strategy based on physical demand, we examined RT as a function of the physical demand associated with the chosen color when the chosen color was attentionally less demanding to find. Although participants found and reported the attentionally less demanding color in each case, they were slower to report the target when its color was associated with greater physical effort demands, $t(8) = 4.42$, $p = .002$, $d_z = 1.47$ (Figure 10B), suggesting that they may have tended to find it only after initially searching for and failing to find a target in the physically less demanding color, essentially "giving up" on the more difficult search at some point in order to more quickly complete their search.

Discussion

Experiment 4 demonstrates an effect of both attentional and physical effort demands on the choice of how to conduct a visual search. Participants generally preferred to search for the target in the less prevalent color, which was associated with a benefit in search performance with respect to RT, suggesting that searching through the less prevalent color was easier than searching through the more prevalent color. This preference was true whether or not participants reported intentionally searching for the less prevalent color. There was also an influence of physical effort demands on which target participants found and reported, which seemed particular to those participants who were consciously aware of the color–effort association and intentionally searched accordingly.

When participants were aware of the fact that reporting a target in a particular color would tend to result in the need to exert relatively high physical effort, they preferred to search for and find a target of the other color even when searching in this way was more attentionally demanding. Importantly, this preference for finding and reporting a target in the color associated with less physical effort was sensitive to demands on attentional effort in visual search, being less pronounced when finding and reporting the color associated with greater physical effort was less attentionally demanding. That is, participants were increasingly willing to engage in a visual search strategy that would bring about the need to exert greater physical effort the more difficult the alternative strategy would be with respect to the attentional demands of finding a target. The effect of attentional demand, in contrast, could proceed without a deliberate strategy and may have been influenced by the relative salience (feature contrast) of the less prevalent color (see Discussion of Experiment 5 for further treatment of the issue of salience).

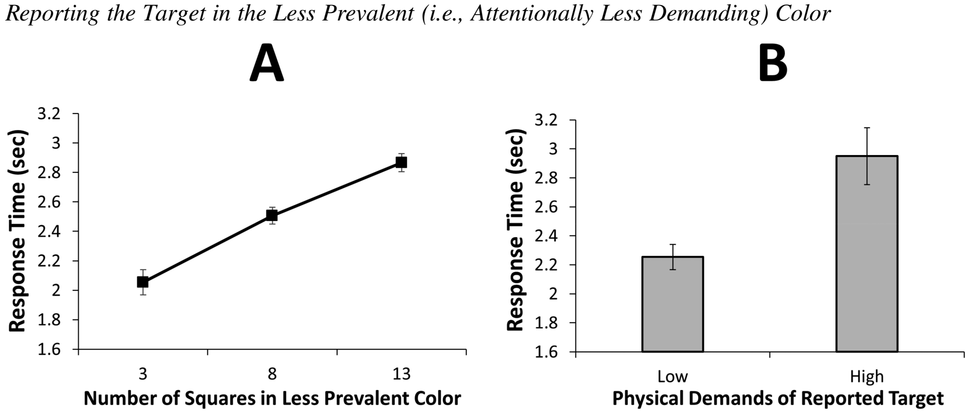
The selectivity of the effect of physical effort in participants who reported consciously using such an effort-based strategy suggests an effect of color–effort associations on strategic, goal-directed attention specifically. It does not seem to be the case that implicit associations between color and physical effort bias attention in favor of the low-effort color or against the high-effort color in our task, in the same manner that associations between color and reward or punishment can bias feature-based attention (e.g., Grégoire et al., 2022; Grégoire & Anderson, 2019; Leganes-Fonteneau et al., 2018, 2019; see Anderson et al., 2021, for a review). This lack of an effect of effort associations in unaware participants may reflect the fact that learning from effort exertion does not engage the same associative learning mechanisms as learning from reward and punishment (e.g., aversive electric shock), or it may simply stem from the fact that the ACVS paradigm is designed to measure the choice and consequence of attentional control strategy. That is, the ACVS paradigm may not be sensitive to implicit or more stimulus-driven attentional biases, the impact of which is typically strongest in the early stages of visual information processing (Anderson & Kim, 2019; Donk & van Zoest, 2008; Godijn & Theeuwes, 2002; Kim & Anderson, 2022; Nissens et al., 2017; Pearson et al., 2016; van Zoest et al., 2004; but see Britton & Anderson, 2021) and may have minimal influence over more sustained attentional processes such as those that are responsible for localizing a target in this task (see also Lee et al., 2022).

Experiment 5

The influence of physical effort demands on visual search strategy seemed contingent upon awareness of the color–effort associations

Figure 10

Response Time in Experiment 5 as a Function of (A) Attentional Demands (Ratio of Less Prevalent to More Prevalent Color) Collapsed Across Physical Demands and (B) Physical Demands When Reporting the Target in the Less Prevalent (i.e., Attentionally Less Demanding) Color



Note. Error bars reflect the standard error of the mean (SEM).

in Experiment 4, with aware participants constituting the minority of our sample ($n = 9$). To replicate the effect of physical effort demands on the willingness to engage in a more difficult visual search with a larger sample, we conducted an experiment that was similar to Experiment 4 except that participants were given complete information about the relationship between color and both attentional and physical effort demands. Experiment 5 also served to bring our experimental approach more in line with that of Experiments 1–3 in which participants operate with full awareness of task contingencies and have the opportunity to explicitly consider how they will choose to behave in light of those contingencies before they begin performing the task. To this end, in Experiment 5, participants were informed that on each trial there would be more red than blue squares or more blue than red squares and that it is easier to find the target of which there are fewer squares rendered in that color. Participants were also informed that reporting one of the two target colors would cause them to have to grip the hand dynamometer harder. The contingencies were set to 100% such that reporting one color always resulted in the difficult physical effort requirement and reporting the other always resulted in the easy physical effort requirement. Beyond being informed of these color–effort relationships, participants were simply instructed to search for whichever of the two colors they wanted to on any given trial.

Method

Participants

Nineteen new participants (10 female, 9 male; $M_{age} = 18.8$ years, [$SD = 1.2$ years]) were recruited from Texas A&M University, using the same compensation and inclusion criteria. A sample size of $n = 18$ was targeted to provide power $(1 - \beta) > 0.9$ with $\alpha = .05$ to replicate the main effect of attentional effort and the main effect of physical effort in participants who reported using an effort-based strategy from Experiment 4; due to scheduling considerations, data from one additional participant was also collected and therefore included in the final analysis.

Apparatus, Calibration, Stimuli, Design, Procedure, and Data Analysis

Identical to Experiment 4 with the following exceptions. Participants were informed that on each trial, there would be more red than blue squares or more blue than red squares and that it is easier to find the target of which there are fewer squares rendered in that color. Participants were also informed that reporting one of the two target colors would cause them to have to grip the hand dynamometer (or "grip device") harder. The contingencies were set to 100% such that reporting one color (counterbalanced across participants) always resulted in the difficult grip requirement and reporting the other always resulted in the easy grip requirement. Beyond being informed of these color–effort relationships, participants were simply instructed to search for whichever of the two colors they wanted to on any given trial. Since participants were informed of the task contingencies, there was no assessment of strategy.

Results

Overall accuracy in the task was 95.7%, indicating that participants generally reported a valid target within the time limit provided.

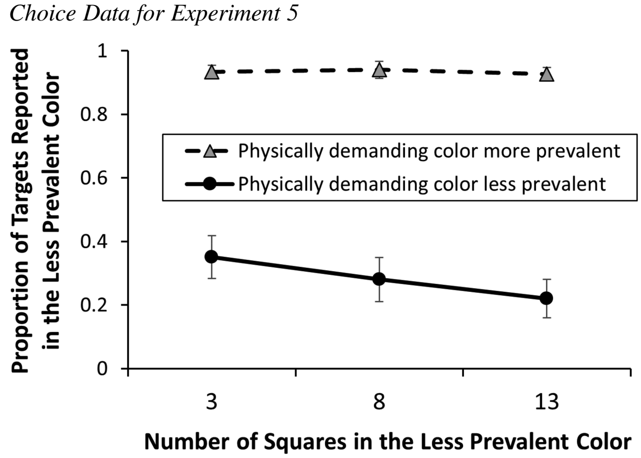
As in Experiment 4, there was a main effect of attentional demand, $F(2, 36) = 16.09$, $p < .001$, $\eta_p^2 = 0.472$, and physical demand, $F(1, 18) = 78.98$, $p < .001$, $\eta_p^2 = 0.814$ (Figure 11). Unlike Experiment 4, the interaction was significant, $F(2, 36) = 16.01$, $p < .001$, $\eta_p^2 = 0.471$. As is evident from the figure, participants reported the physically less demanding color nearly all of the time regardless of the specific distribution of red-to-blue stimuli, likely reflecting a ceiling effect with respect to attentional demand, but report of the physically demanding color was influenced by this distribution as in Experiment 4. This was borne out in the simple main effect of attentional demand at each level of physical demand, which was not significant for the physically less demanding color, $F(2, 36) = 0.60$, $p = .552$, but robustly significant for the physically demanding color, $F(2, 36) = 21.43$, $p < .001$, $\eta_p^2 = 0.544$. That is, when the easier-to-find target was rendered in the physically demanding color, the easier this target was to find, the more willing participants were to find and report it despite the subsequent demands on physical effort brought about by this choice.

The overall effect of color prevalence and physical demand on RT was fully replicated from Experiment 4 (all ps $< .001$). That is, participants were again faster to report the target as a function of the number of squares presented in the less prevalent color, verifying the relationship between color prevalence and attentional demands, and were slower to report a target in the less prevalent color when it was associated with greater physical demand.

Finally, we compared RT for trials on which a target rendered in the physically less demanding color was reported and (a) there were only three stimuli rendered in this color (i.e., it was the attentionally less demanding target to find and report) and (b) there were 37 stimuli rendered in this color (i.e., it was the attentionally more demanding target to find and report). The difference between these two conditions provides the putatively most extreme estimate of the RT cost of choosing to search for the more difficult-to-find target in order to avoid the high physical effort requirement. This comparison resulted in a mean difference of 1,567 ms (Ms = 1,626 vs. 3,193 ms, SDs = 605 vs. 432 ms), which was considerably smaller than the 3 s grip requirement associated with high physical effort (this was individually true for 17 of 17 participants [note that two

Figure 11

Choice Data for Experiment 5



Note. Error bars reflect the standard error of the mean (SEM).

participants only ever reported a target in the less prevalent color on such trials, resulting in no valid samples for (b), and were thus excluded from this analysis]). Thus, for the sake of minimizing the overall duration of the experiment, it would not be in the participants' best interest to search for and report the target of the physically more demanding color even when stimuli of this color were less numerous and thus easier to search through, yet participants frequently took the easier road with respect to visual search to the detriment to both physical effort demand and the total duration of the trial, increasingly so as attentional demands decreased for finding and reporting the physically more demanding color.

Discussion

Experiment 5 replicates the main finding from Experiment 4 in that both physical effort and attentional effort considerations influenced how participants chose to search (the main effect of each factor). In this case, we also observed a significant interaction between physical effort and attentional effort, likely stemming from the fact that participants almost exclusively reported a target rendered in the physically less demanding color when this color was the attentionally less demanding color to search through, regardless of the exact color distribution (ceiling effect). When the attentionally and physically less demanding colors were different on a given trial, participants were more willing to find and report the physically more demanding target as it became increasingly less attentionally demanding to find.

A question can be raised concerning why we observed a significant interaction between attentional and physical effort considerations in Experiment 5, while in Experiment 4 these considerations exerted an additive influence on performance. In Experiment 5, with full awareness of the contingencies (which more closely mirrors the conditions of Experiments 1–3), participants would have known explicitly when physical and attentional effort considerations are aligned or in conflict, which likely influenced their strategy selection, producing highly consistent preferences when these considerations were aligned and some measure of a tradeoff when they were not. We also note that an influence of physical effort considerations on performance was only observed in participants who were aware of the color–effort association in Experiment 4; all of the unaware participants and an unknown number of trials prior to noticing the association for aware participants would be expected to evidence only a main effect of attentional effort without an effect of physical effort considerations, which would drive the data away from an interaction. Aware participants may have also wavered in their confidence that color and physical effort were related, possibly tending to focus on one rule/relationship at a time. We therefore believe that the interaction observed in Experiment 5 is a better reflection of how participants choose to search when they are explicitly balancing effort considerations, as in the first three experiments.

Interestingly, the RT cost of reporting the physically less demanding color even when it was maximally attentionally demanding to do so (i.e., required the maximum number of items to be searched) was on average well below the 3 s requirement associated with the more difficult grip task. Were participants making decisions concerning how to search that were exclusively driven by a desire to complete the experiment as quickly as possible, reporting the target in the physically more demanding color would have been counterproductive regardless of how easy a target of this color was to find. It therefore seems unlikely that the findings from Experiment 5 can be explained by an explicit strategy to minimize the duration of the experiment, which is consistent with the findings from Experiment 3. Participants may not have been aware of the average time to complete a trial using different search strategies, and as further expounded upon in the "General Discussion" section, we suspect that all else being equal, participants would be motivated to minimize the duration of the experiment. We do not mean to imply that the desire to minimize attentional effort at times overshadowed a desire to minimize the duration of the experiment, only that participants evidenced a drive to minimize attentional effort in Experiment 5 that does not appear to be reduceable to the consequences of a strategy to complete the experiment as quickly as possible.

It might be argued that the search behavior observed in this experiment was to some degree the product of a demand characteristic brought about by the explicit manipulation of effort. That is, because participants were informed about both sources of effort and their associated task contingencies, they may have felt that they were expected to incorporate both of these factors into their decision-making (despite the fact that they were explicitly told that they should search however they saw fit). That a joint influence of physical and attentional effort on visual search performance was observed for participants who were not informed of the task contingencies in Experiment 4 argues against this interpretation as providing a complete account of our data, and it is interesting to know how people choose to search when they can wholly anticipate the consequences of their actions. With that said, however, the specific magnitude of effect observed in Experiment 5 may be to some degree biased by participants' feeling like they should be influenced to a nonzero degree by both sources of effort.

It is worth considering the concept of attentional demand more closely in this and the prior experiment. Our definition of attentional demand assumes that participants actively enumerate the displays in order to determine which color is the less prevalent one before searching. This enumeration process is likely itself at least somewhat attentionally demanding (see Hansen et al., 2019), and in this context, it could be argued that the least attentionally demanding way to approach the task would be to search without respect for the distribution of color stimuli. The fact that there was a robust influence of the different color distributions, with participants being significantly more likely to report a target as its color became less prevalent, suggests that participants were sensitive to this manipulation, making the comparison of the attentionally more and less demanding color meaningful. Especially at more extreme distributions (i.e., 3/37), stimuli rendered in the less prevalent color were also likely perceived as more physically salient (higher feature contrast, see Itti & Koch, 2001; Theeuwes, 1992, 2010), which may have influenced search. To the extent to which the physical salience of stimuli rendered in the less prevalent color influenced search, however, it would have served to bias attention in favor of the less prevalent color stimuli, which would be in accord with our conceptualization of attentional demand (i.e., color stimuli with higher attentional priority by virtue of their physical salience should be less demanding to search for).

General Discussion

What makes a task mentally effortful? The amount of information that must be maintained in working memory and the degree to which cognitive control mechanisms need to be engaged are well established to contribute to the mental effort of a task (e.g., Kool et al., 2010; Vogel et al., 2020; Westbrook et al., 2013). Selectively processing task-relevant perceptual information while ignoring irrelevant information is a ubiquitous part of both everyday and laboratory tasks, but the cognitive demands associated with this requirement have scarcely been considered in the study of mental effort. Given that visual search relies on low-demand and potentially largely automatic attentional processes (see Anderson, 2018) and that attentional processes in visual search may be optimized to minimize the need for controlled and effortful processes (Anderson, 2021), there is reason to think that conducting a visual search might not tax mental effort in a meaningful way. Yet, there is considerable theory concerning what makes a visual search task more difficult from the standpoint of the efficiency of performance (e.g., Duncan & Humphreys, 1989; Huang & Pashler, 2005; Hulleman, 2010; Wolfe, 2020; Wolfe et al., 1989), which may be related to mental effort.

Different conditions under which people perform a visual search can give rise to different degrees of efficiency in performance, and individuals differ in the efficiency with which they can find and report a target given a particular set of conditions. Do these differences map onto variation in the amount of mental effort involved in completing the search? In the present study, we created situations in which physical and mental effort could trade-off, with the logic that, the more effortful a visual search task, the more willing participants would be to exert physical effort in order to reduce the demands of searching. Throughout five experiments, we find evidence that visual search is indeed effortful, trading off with physical effort demands in a manner that mirrors theoretical conceptions of search difficulty. People will physically work to reduce the demands of visual search, working physically harder as putative visual search demands increase. Likewise, people will voluntarily engage in an easier visual search even if it means that doing so will beget a more demanding physical effort requirement, increasingly so as the more physically demanding search strategy becomes attentionally less demanding.

Visual search is sometimes described as "difficult" or "easy" on the basis of search slope and/or set size (e.g., Duncan & Humphreys, 1989; Huang & Pashler, 2005; Hulleman, 2010; Wolfe, 1998, 2020; Wolfe et al., 1989), with search slope being affected by factors such as nontarget heterogeneity (Duncan & Humphreys, 1989). In the present study, we provide objective evidence using measurements of physical force expenditure that these factors can be mapped onto conceptions of mental effort. As search slopes become steeper and search set size increases, people are increasingly willing to exert physical effort in order to reduce the number of items that need to be searched. Likewise, as the set size for one color decreases, people are increasingly willing to search for and report a target of that color despite the physical demands incurred for doing so. The present study targeted canonical indicators of the "difficulty" of visual search tasks, relating them to the attentional effort, which are subject to further specifications that could be the target of further investigation. For example, future research might seek to disentangle the extent to which more executive attentional processes (e.g., maintaining and applying a target template that efficiently discriminates between targets and nontargets) versus lower-level attentional processes (e.g., targeting and executing eye movements) are responsible for the perceived attentional effort required of a visual search task.

When given a choice, participants will sometimes choose to endure physical pain in order to avoid having to complete a brief but cognitively demanding task, and the more cognitively demanding the task, the more pain participants are willing to endure in order to avoid having to complete the task (Vogel et al., 2020). Likewise, rewards are devalued as a function of the cognitive effort required to obtain them (Apps et al., 2015; Westbrook et al., 2020). The choice of which of two cognitive tasks to perform is influenced by the cognitive demand associated with each, with participants exhibiting a bias toward the less demanding task (Kool et al., 2010). Our findings may reflect a similar principle with respect to a drive to minimize cognitive or mental effort, extending this idea to the control of attention in visual search.

In Experiments 1 and 2, exerting physical effort not only served to reduce the search set size, thereby reducing the amount of effort required to find the target, but it also allowed the target to be found more quickly. Since the next trial started immediately after the current trial had been completed, exerting physical effort in these experiments effectively reduced the total duration of the experiment. People consider time to be a valuable resource, valuing the faster completion of a required task for the consequent freedom to invest the "saved" time as they see fit (Hamermesh, 2019). Consistent with this valuation, where our experiments reframed such that exerting physical effort would shorten the duration of the experiment by shortening the ITI, we suspect that people would exert physical effort for the sole sake of completing the experiment faster. The question can then be raised concerning to what degree this same motivation contributed to participants' willingness to exert physical effort in order to reduce the search set size, which would have little if anything to do with mental effort per se. Experiment 3 explicitly ruled out such motivation as providing a complete account of participants' willingness to exert physical effort, as the overall pattern of results with respect to the physical effort was replicated even when exerting physical effort could do nothing to shorten the duration of the experiment (and participants were explicitly informed of this). Experiments 4 and 5 seem less susceptible to a drive to minimize the duration of the experiment as providing a complete account of why participants' chose to search the way they did, since finding the physically more demanding target tended to prolong the experiment even when it was the easier/faster of the two targets to find (given the time needed to fulfill the more demanding physical effort requirement).

Experiments 4 and 5 have additional implications for our understanding of the mechanisms governing the control of attention. We provide evidence that effort minimization serves as a guiding principle with respect to these mechanisms. When visual search can proceed in more than one way in order to achieve a desired end, the manner in which it does proceed reflects a bias to minimize the amount of both physical and mental effort. When a physically demanding target is easy to find, people are more likely to endure the added physical demands in exchange for easing the attentional burden of a visual search. Such a result is consistent with the function of attentional control as conceptualized by Anderson (2021).

Particularly in the context of the preview display, during which participants can exert physical effort in order to reduce the demands of the upcoming visual search task, our findings bear some resemblance to the phenomenon of *precrastination* by which individuals endeavor to complete work requirements sooner rather than later (Rosenbaum et al., 2014; Wasserman & Brzykcy, 2015). Were precrastination, independently of any differences in the perceived effort of visual search across conditions, solely responsible for our observed results, we would not have expected the physical effort participants exerted to vary with set size, display heterogeneity, and individual search efficiency (search slope). A drive toward precrastination was likely related to participants' willingness to exert physical effort more generally, but the extent to which physical effort expenditure scaled with putative attentional demands affirms that people are sensitive to such demands. Likewise, a large number of studies affirm the idea that people can be "cognitive misers," endeavoring to limit the amount of mental effort exerted (e.g., Allport et al., 1954; Hull, 1943; Rosch, 1999; Solomon, 1948; Zipf, 1949), and our study is consistent with this conceptualization. In extending the concept of the cognitive miser to visual search, we provide novel evidence concerning what makes a task mentally effortful in a way that people would be motivated to avoid or mitigate.

Our findings have implications for how we think about the demands of visual search in everyday life. These findings suggest a direct analogy between the conduct of visual search and physical effort. For individuals who repeatedly perform visual searches in the context of their profession, for example, radiologists searching x-ray images for signs of cancer or Transportation Security Administration officers searching baggage for contraband, these demands may be significant. Although exactly how visual search compares to other cognitive tasks with respect to mental effort reflects an interesting question for future research that is explored from a methodological standpoint in the following paragraph, the present study suggests that visual search should be considered as objectively mentally effortful, establishing the viability of conceptualizing visual search as effortful mental work. It may be prudent to consider how long we ask people to perform repetitive visual searches and what steps are taken to ensure adequate recovery time, in a similar manner to how physical labor demands are managed.

The experimental approach that we developed for the present study is novel and could be extended to a broad range of cognitive tasks beyond visual search to provide an objective measurement of how effortful people find such tasks to be. This could be tested both with respect to dimensions of a task that are hypothesized to map onto mental effort (as in the present study) as well as with respect to whether different manipulations (e.g., training) reduce the effort involved in the performance of a task. Different tasks could be intermixed and compared to assess which of the two (or more) is more effortful to perform. The effects of prior task performance on willingness to exert physical effort in subsequent trials could be examined in order to gain a window into the effects of mental fatigue, which could be examined both within the same task and also across tasks to test questions about domain-general cognitive fatigue. By trading off the performance of a cognitive task with the expenditure of physical effort, a variety of new vistas concerning cognitive/mental effort can be opened that may provide fundamental new insights.

Open Practices Statement

The experiments reported in this article were not formally preregistered. Neither the data nor the materials have been made available on a permanent third-party archive; requests for the data or materials can be sent via email to the lead author at Email: brian.anderson@tamu.edu.

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