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When Detecting a Salient Target Makes Search More Effortful

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Prior research has demonstrated two distinct modes of searching a display: singleton detection mode and feature search mode. Due to the explicit template-based attentional control involved in feature search mode, singleton detection mode is often assumed to be less mentally effortful, which can potentially explain why people search using such an inefficient and distraction-prone strategy. However, this assumption remains largely untested. In the present study, we used a hand dynamometer to relate physical effort to perceived mental effort across different search conditions. Surprisingly, across three experiments, participants exerted more effort to avoid singleton detection trials compared to feature search trials, suggesting that they found singleton detection to be the more effortful mode of searching. In a fourth experiment, we removed the physical effort component and simply asked participants to self-report how effortful they perceived each search task to be. Participants robustly indicated that singleton detection trials were more effortful. Lastly, in a fifth experiment, we removed distractor-present trials. Again, participants exerted more effort to avoid singleton detection trials. In contrast to widely held assumptions, our findings suggest that searching for a salient singleton is in fact more mentally effortful than searching for a specific feature in a heterogeneous display, which has broad implications for theories of attentional control and the influence of mental effort on cognition.

Public Significance Statement

People sometimes search in a way that is susceptible to distraction, even when there are more efficient ways the person could search. It has long been assumed that people engage in inefficient search strategies because these strategies are less mentally effortful. Here, we provide evidence suggesting the exact opposite. Our data show that people can sometimes default to the use of search strategies that are suboptimal from the perspective of both search efficiency and effort minimization, providing novel insights into why people can become distracted.

Keywords: attentional capture, visual search, search modes, mental effort, physical effort

In everyday life, we interact with visual scenes composed of a variety of stimuli. Because these stimuli often compete for limited cognitive resources, attention is necessary to selectively process this information (Desimone & Duncan, 1995). A number of factors have been shown to influence the process of attentional selection, including stimulus-driven and goal-directed factors (Corbetta & Shulman, 2002; Theeuwes, 2010). For example, both visual salience (Theeuwes, 1992; Yantis & Jonides, 1984) and observers' current goals (Bacon & Egeth, 1994; Folk et al., 1992) have been shown to influence the allocation of attention. Recent evidence suggests that prior experience, or selection history, can also influence this attentional selection process (Anderson et al., 2021; Awh et al., 2012). Together, these findings offer important insights regarding the nature of attentional control and provide a foundation for theoretical frameworks conceptualizing how visual search progresses (e.g., Wolfe, 2020; Wolfe & Horowitz, 2017).

Perspectives on How We Search

A long-standing debate in the attention literature concerns the conditions under which certain types of stimuli can involuntarily capture attention. According to stimulus-driven theories of attention, salient stimuli can automatically capture attention regardless of observers' current goals (Franconeri & Simons, 2003; Theeuwes,

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1992; Yantis & Jonides, 1984). Evidence for this position predominantly comes from studies using the additional singleton paradigm. For example, in an influential study, Theeuwes (1992) had participants search for a unique shape among homogeneous nontargets and identify the orientation of a line located inside this shape. On some trials, a uniquely colored distractor (a color singleton) was also present in the display. Critically, participants were slower to respond when this color singleton was present, even though it was never the target and participants were instructed to ignore this item. Based on these findings, many researchers have concluded that color singletons and other salient stimuli can automatically capture attention (e.g., Theeuwes, 2010).

Although the previous findings provide compelling evidence for stimulus-driven theories of attention, this is not the only position in the attentional capture debate. According to goal-directed theories of attention, salient stimuli will only capture attention when they match observers' current goals (Bacon & Egeth, 1994; Folk et al., 1992, 2002). For example, Bacon and Egeth (1994) noted that because the target in many additional singleton studies is a shape singleton, participants in these studies could have searched for any unique item in the display, resulting in attentional capture by other salient stimuli. Based on this observation, two distinct search modes were hypothesized: singleton detection mode and feature search mode (see also Pashler, 1988). While singleton detection mode prioritizes items based on their salience, feature search mode prioritizes items based on their specific features. To test whether the use of singleton detection mode could explain Theeuwes's (1992) findings, the researchers encouraged participants to adopt feature search mode by having them search for a specific shape among heterogeneous nontargets. Critically, under these conditions, participants were not slower to respond when a color singleton distractor was present, suggesting that they were able to override attentional capture by salient stimuli and restrict attention to stimuli possessing a specific feature.

The idea that these two manners of searching could be characterized as strategic search modes was further supported by experience-dependent effects on search performance. When either mode of searching (on the basis of a specific feature or on the basis of a salient singleton) is possible, prior experience requiring the use of one of the two modes of searching determines whether performance is consistent with feature search or singleton detection (Cosman & Vecera, 2013; Leber & Egeth, 2006a, 2006b; Leber et al., 2009). For example, Leber and Egeth (2006b) trained participants in the use of singleton detection or feature search mode, then had them complete a series of "option trials" on which either search mode could be used. Critically, participants who were trained in the use of singleton detection mode showed a robust distractor cost on these trials, while participants who were trained in the use of feature search mode did not. That is, when presented with the same visual displays, how a person proceeded to search was found to be the product of the approach to search that they had become familiar with in the experiment. These findings provide strong evidence for an endogenous influence on how attentional processing proceeds.

While the previous findings can be explained by the use of different search modes, there are alternative explanations for these findings. Most prominently, Theeuwes (2004) proposed that these findings can be explained by the use of a variable-size attentional window. According to this account, observers can explicitly set the size of the attentional window based on task demands, restricting attentional processing to stimuli within the window. Salient stimuli within this window will be prioritized, while stimuli outside this window (salient or otherwise) will be ignored. Theeuwes hypothesized that observers use a smaller attentional window in heterogeneous displays, resulting in reduced attentional capture by salient stimuli outside this window. However, using a smaller attentional window requires observers to engage in serial search, resulting in increased search times as the number of items in the display increases. In contrast, Theeuwes hypothesized that observers use a broader attentional window in homogenous displays, resulting in attentional capture by salient stimuli within this window. Critically, this account can explain many of the previous findings without assuming the use of different search modes (see also Belopolsky & Theeuwes, 2010; Belopolsky et al., 2007).

Explaining Variable Manners of Searching: The Question of "Why?"

Although attempts to reconcile these two conflicting perspectives on how people search have been made (Gaspelin & Luck, 2018b; Gaspelin et al., 2015, 2017), the idea that individuals would prioritize targets on the basis of their physical salience remains a point of controversy (e.g., Luck et al., 2021). Regardless of whether previous findings are better explained by the use of different search modes or a variable-size attentional window, however, we must grapple with the fact that observers are in some situations searching in a manner that renders them more vulnerable to attentional capture. Another finding that has received far less discussion in the literature but is also relevant to this issue is that the search for a singleton target tends to be generally slower than the search for a feature-defined target in a heterogeneous display (e.g., Leber & Egeth, 2006b). However people are searching when they search for a physically salient target, be it with respect to prioritizing salient stimuli or broadening the size of their attentional window, their manner of searching constitutes a demonstrably inefficient approach as far as task performance is concerned. This naturally raises the broader question of why people would ever search in this manner in the first place.

As controversial as the issue of "how" has been in theories of attention, the answer to the question of "why" has been more or less taken for granted on both sides of the debate and centers on the concept of mental effort. As Bacon and Egeth (1994) originally proposed, people likely prioritize salient stimuli when the target is itself salient because it is simply easier to do so, sacrificing the efficiency of search performance for reduced cognitive demand. At a minimum, searching for a specific target feature requires maintaining a template for the target stimulus in active memory (Woodman et al., 2013) and comparing this template against perceptual input. It requires actively engaging in a goal-directed cognitive process (Wolfe, 2020, 2021). Directing attention to salient stimuli is presumably a comparatively passive process, especially if the attentional system defaults to prioritizing salient stimuli in the absence of an explicit target template (e.g., Bacon & Egeth, 1994; Lamy & Egeth, 2003). When it comes to searching for a physically salient target, observers more or less "allow" their attention to be directed to salient stimuli until they happen upon what they are looking for. This idea can be just as readily applied to why people would prioritize targets on the basis of their physical salience as it can to why they would search using a broad attentional window. Search in heterogeneous displays is also known to be less efficient or more "difficult" than search in homogeneous displays (Duncan & Humphreys, 1989; see also Anderson & Lee, 2023), with the choice of search mode or the size of the attentional window potentially reflecting a response to such demand.

Although no study has directly tested whether one mode of searching is more mentally effortful than another, many theories assume that mental effort is costly (Shenhav et al., 2017; Westbrook & Braver, 2015), analogous to the costs associated with physical effort (Cheval & Boisgontier, 2021; Lieberman, 2015). When given the option, people generally prefer tasks that minimize physical effort (Klein-Flügge et al., 2016; Kurniawan et al., 2010; Prévost et al., 2010), which is thought to reflect an adaptive tendency to conserve energy resources for potential use in the future (Cheval & Boisgontier, 2021; Lieberman, 2015). Extending this idea into the domain of human cognition, a number of studies suggest that observers often avoid performing mentally effortful tasks (Kool et al., 2010; Vogel et al., 2020; Westbrook et al., 2013), and attempt to achieve an optimal balance between effort and other factors, such as reward (Apps et al., 2015; Clay et al., 2022; Dixon & Christoff, 2012; Westbrook et al., 2013, 2020), leisure (Kool & Botvinick, 2014), and punishment (Vogel et al., 2020). Lastly, there is evidence that observers adopt search strategies that minimize effort, even if these strategies are inefficient (Irons & Leber, 2016, 2018). It has been argued that one of the overarching principles governing the control of attention is the minimization of the need for controlled and effortful processes (Anderson, 2021). It is possible that people search visual displays in a manner that minimizes the mental effort required to find the target, and that searching for a salient singleton is comparatively inefficient because individuals are sacrificing efficiency for the opportunity to engage in a low-effort search process driven by salience.

The Present Study

The idea that people find searching for salient stimuli or searching with a broad attentional window less effortful than more restrictive modes of allocating attention has never been tested. This is perhaps unsurprising in light of the uncontroversial nature of this idea, in the context of a literature otherwise fraught with controversy (Luck et al., 2021). Findings in the affirmative would help explain why individuals are so ostensibly prone to distraction in certain situations: A significantly reduced search efficiency would be more understandable in the context of a less effortful search process.

We recently developed a novel method for comparing the mental effort involved in two or more search contexts (Anderson & Lee, 2023). By creating a situation in which exerting physical effort can influence the mental effort required of a search task, one can compare how much physical effort a participant exerts across different task conditions to identify which are the most mentally effortful: The more mentally effortful the visual search task, the more motivated people should be to exert physical effort to offset some of the additional mental demand. Indeed, a similar method has been used to compare the mental and physical effort involved in different tasks (Feghhi & Rosenbaum, 2019; Feghhi et al., 2021; Potts et al., 2018). In the present study, we adapted this approach to the context of search conditions conducive to feature search and singleton detection. For the remainder of the article, we will refer to trials in which a shape-defined target is presented among heterogeneous nontargets as feature search trials and trials in which a shape singleton target is presented among nontargets that are homogeneous with respect to shape as singleton detection trials, agnostic as to whether a variable-size attentional window and/or a strategic prioritization of salient stimuli characterizes the associated mode of searching (as they each make the same predictions with respect to the underlying mental effort involved in searching). We hypothesized that participants would find singleton detection trials less effortful than feature search trials, working physically harder to reduce the need to perform feature search.

Experiment 1

In Experiment 1, participants alternated between completing mini-blocks of feature search trials and singleton detection trials, which varied in length from eight to 32 trials. Before each mini-block, they were provided the opportunity to reduce the number of trials in the mini-block by up to half, by exerting physical effort using a hand dynamometer. We expected to replicate evidence that singleton detection mode is less efficient, resulting in larger distractor costs and generally longer response times (RTs) in target identification, even in the absence of a distractor (Leber & Egeth, 2006b). We further expected that participants would be generally motivated to reduce the number of trials they needed to complete, increasingly so as the length of the mini-block increased (and with it, the number of trials that could be eliminated by exerting physical effort). Importantly, we also expected that participants would be even more motivated to reduce the number of trials they needed to complete for the search task that they found to be more mentally effortful, exerting more physical effort in advance of these particular mini-blocks. Consistent with widely held assumptions in the field (Bacon & Egeth, 1994; Lamy & Egeth, 2003, 2006a, 2006b; Leber et al., 2009), we hypothesized that participants would exert more physical effort in advance of feature search mini-blocks, in line with the idea that feature search mode is the more effortful mode of searching.

Method

Participants

Forty participants were recruited from the Texas A&M University community (25 female, 15 male, $M_{\text{age}} = 18.9$ years [$SD = 1.5$ years]). Participants were compensated either with course credit or $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 $(1 - \beta) > 0.9$ with $\alpha = .05$ to detect an effect of task demands on effort of the magnitude reported in Anderson and Lee (2023; computed using G*Power 3.1; Faul et al., 2007).

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

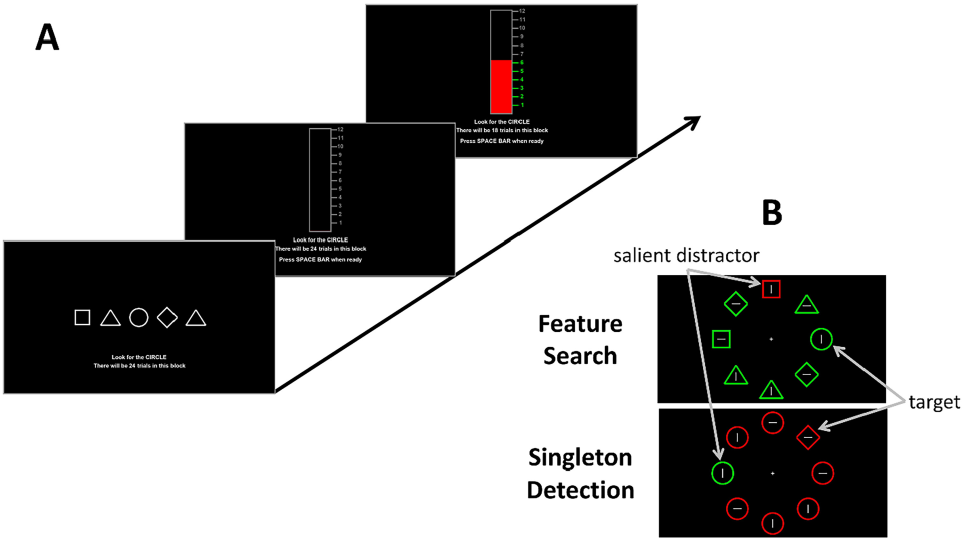
Participants performed the same calibration task used by Anderson and Lee (2023), which was adapted from Park et al. (2021). Participants squeezed the hand dynamometer as hard as they could using their left hand over three trials to determine their individually calibrated grip strength. Each trial was 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).

Stimuli

Each trial during the search task consisted of a search array and a blank intertrial interval (ITI). The search array consisted of a white plus sign (0.5° × 0.5°) presented at the center of the screen against a black background along with eight outline shapes each containing an internal line segment (see Figure 1). For singleton detection trials, the shapes consisted of a single diamond among seven circles or a single circle among seven diamonds. For feature search trials, the shapes consisted of one circle, three triangles, two diamonds, and two squares. The shapes were sized to be closely matched for diameter/circumference (with the square subtending 2.9° × 2.9°), positioned at equal intervals along an imaginary circle with a radius of 7.6°. The outline shapes were rendered in either red or green; the internal line segments consisted of vertical or horizontal white bars, 1.3° in length. In the event of an incorrect response or a timeout, an additional feedback display was inserted between the search array and ITI that consisted of the words "Incorrect" or "Too Slow" presented at the center of the screen in white font.

Before each mini-block, participants were presented with a preview display indicating the upcoming search task, both via text ("Look for the DIFFERENT SHAPE" or "Look for the CIRCLE") and with a set of five outline shapes that served as an iconic representation of the range of shapes that would be encountered, in addition to the number of trials in the upcoming mini-block (see Figure 1). Then, the icon was replaced by the force meter, which comprised a gray outline rectangle (18.7° × 4.1°) that would fill with red as force was applied to the hand dynamometer; additional text stating "Press SPACE BAR when ready" simultaneously appeared at the bottom of the display. The force meter would fill in a manner proportional to the amount of physical force applied to the hand dynamometer, such that applying force equivalent to the individually calibrated force threshold would completely fill the force meter red, applying force equivalent to half of the individually calibrated force threshold would fill half of the force meter red, and so forth. Gray marker lines were set along the right side of the force meter, equally spaced with the number of lines corresponding to half the number of trials for the upcoming mini-block. Each marker line was paired with an adjacent digit, starting with "1" and counting up, reflecting the number of trials that could be removed with physical force. When the force meter filled beyond a given marker line, the marker line and corresponding digit turned green and the number of trials indicated for the mini-block simultaneously decreased. Thus, the amount of force required to remove a trial was proportional to both the individually calibrated grip strength of the participant (to account for individual differences in grip strength) and the number of upcoming trials in the mini-block (since the number of trials that could be removed was scaled to the length of the force meter).

Figure 1
Behavioral Task



Note. (A) Example preview display and force meter for a mini-block in Experiment 1. (B) Example search displays for singleton detection and feature search trials. See the online article for the color version of this figure.

Design

Each mini-block was 8, 16, 24, or 32 trials long before the removal of any trials with physical force applied to the hand dynamometer. Mini-blocks were grouped in sets of eight, with trial length and search task (feature search and singleton detection) fully crossed and counterbalanced. Within a given mini-block, before the removal of any trials with physical force applied to the hand dynamometer, the target appeared in each position equally often, was red and green equally often, was paired with each line orientation equally often, and on singleton detection trials, was a diamond and a circle equally often. The specific combination of these elements across trials was randomized within each mini-block. Half of the trials were distractor-present trials, on which one of the nontargets was rendered in the color not used for the target and the rest of the nontargets, comprising the physically salient distractor. The location of the physically salient color singleton distractor was randomly determined on each distractor-present trial from the locations not occupied by the target. On feature search trials, nontarget shapes were randomly assigned to positions with the constraint that three triangles, two diamonds, and two squares were used. Line segments were randomly assigned to nontargets with the constraint that, including the target, four of the lines were vertical and four were horizontal on each trial. Trials within a mini-block were presented in a random order, and removing *x* trials via physical force amounted to the final *x* trials being omitted from the mini-block.

Procedure

Following calibration of the hand dynamometer, participants completed eight trials of singleton detection and eight trials of feature search without a time limit applied to the search array. Then, participants completed a second practice in which they were introduced to the 2,000 ms time limit and the variable mini-blocks, completing two feature search mini-blocks of 8 and 16 trials and two singleton detection mini-blocks of 8 and 16 trials in a random order. Finally, to conclude practice, participants completed one full set of eight mini-blocks without the force meter. This more extensive practice allowed participants to become robustly familiarized with both search tasks before having the option of exerting effort to reduce the number of trials of a given task that they needed to perform.

Following practice, participants were introduced to the force meter, its relationship to the hand dynamometer, and how the hand dynamometer could be used to reduce the number of trials that they needed to complete for a given mini-block. They were then presented with a demonstration task in which an unspecified mini-block contained 16 trials and they needed to reduce the length by half to progress. This served to ensure that participants understood how to reduce the number of trials in a mini-block. Participants were then instructed that, for each mini-block, how much effort they exerted on the hand dynamometer was entirely up to them. They could reduce the number of trials in the upcoming mini-block by half, choose not to exert any physical effort and complete all of the trials in the mini-block, or anywhere in between.

Participants were not told how many trials long the experiment would be, which was in fact variable. Sets of eight mini-blocks would continue to be generated until 34 min of time had elapsed from the first trial of the main task. This time-dependent task duration prevented participants from completing too few trials if they vigorously applied force to the hand dynamometer consistently or the experiment from going too long if participants elected to apply little if any force. A 30 s break was inserted after each set of eight mini-blocks.

Analytic Approach

We first probed search performance to determine whether searching for a shape singleton target was indeed less efficient than searching for a circle target in a heterogeneous display (feature search). Mean RT and accuracy were each subjected to a 2 × 2 analysis of variance (ANOVA) with distractor presence (present vs. absent) and search mode (singleton detection vs. feature search) as factors. Only correct trials were used in the computation of mean RT and RTs faster than 200 ms or exceeding 3 *SD* of the conditional mean were trimmed as outliers. For mean RT, in the event of a significant main effect of search mode, we performed an a priori targeted contrast comparing distractor-absent trials for each search mode to determine whether singleton detection mode resulted in slower performance that could not be attributed to distractor-related slowing (i.e., attentional capture). In the event of a significant main effect of distractor presence on RT, we additionally performed a priori contrasts comparing distractor-present and distractor-absent trials separately for each search mode to determine whether a significant effect of the distractor was present in each case.

We next probed physical effort exertion to determine the conditions under which participants exerted the most effort. Effort was quantified for each mini-block as the peak effort measured on the hand dynamometer in advance of the mini-block, expressed as a proportion of the participant's calibrated maximal effort, up to 1.0 on a given mini-block. Then, mean peak effort was computed as a function of the upcoming search task (singleton detection vs. feature search) and the number of trials that the mini-block would contain without any physical force applied (block length: 8, 16, 24, 32) for each participant and subjected to a 4 × 2 ANOVA with block length and search mode as factors. All statistical analyses were performed using JASP 0.16.0.0 (JASP Team).

Transparency and Openness

The experiments reported in this article were not formally preregistered. Raw data for all experiments are available via the Open Science Framework at https://osf.io/d3bxt/.

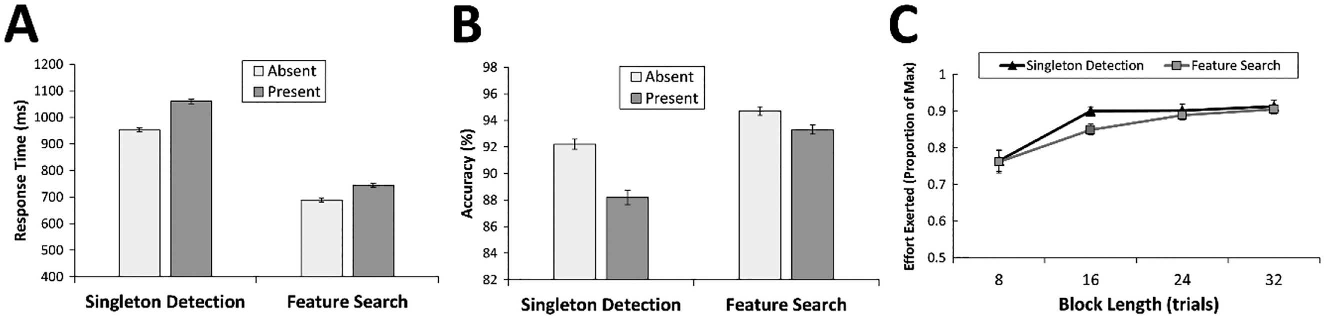
Results

Search Performance

An ANOVA on RT revealed a main effect of distractor presence, $F(1, 39) = 363.37$, $p < .001$, $\eta_p^2 = .903$, reflecting attentional capture by the salient distractor (Figure 2A). There was also a main effect of search mode in which RT was overall slower on singleton detection trials, $F(1, 39) = 413.65$, $p < .001$, $\eta_p^2 = .914$. This slowing was evident even when restricting analyses to distractor-absent trials, $t(39) = 18.70$, $p < .001$, $d_z = 2.96$, consistent with the idea that searching for a salient singleton is generally inefficient. There was also a significant interaction between distractor presence and search mode, $F(1, 39) = 52.77$, $p < .001$, $\eta_p^2 = .575$, reflecting greater vulnerability to attentional capture on singleton detection

Figure 2

Results for Experiment 1



Note. (A) Mean RT, (B) mean accuracy, and (C) mean physical effort exertion. Error bars in all panels reflect ±1 within-subjects standard error (Cousineau, 2005; Morey, 2008). RT = response time; ms = milliseconds; max = maximum.

trials. The distractor presence cost was individually significant on both singleton detection, $t(39) = 15.67$, $p < .001$, $d_z = 2.48$, and feature search trials, $t(39) = 13.68$, $p < .001$, $d_z = 2.16$. An ANOVA on accuracy mirrored this pattern, with the same main effects and interaction, $Fs > 13.22$, $ps < .001$ (Figure 2B).

Physical Effort Exertion

As expected, there was a main effect of block length in which participants generally exerted more effort as the mini-blocks became longer, $F(3, 117) = 10.47$, $p < .001$, $\eta_p^2 = .212$ (Figure 2C). Most critically, there was also a main effect of search mode, $F(1, 39) = 4.59$, $p = .039$, $\eta_p^2 = .105$, which was in the direction opposite of what was predicted; participants exerted more physical effort to reduce the number of singleton detection trials. The interaction between block length and search mode was marginally significant, $F(3, 117) = 2.26$, $p = .085$. Numerically, the difference between search modes was the most pronounced for the 16-trial mini-blocks, by which point the exertion of physical effort had reached asymptote for singleton detection trials. The observed difference in physical effort exertion between search conditions translated to participants completing an average of 5.5 ($SD = 16.9$) fewer singleton detection than feature search trials.

Discussion

We replicated evidence that search is less efficient when the target is a shape singleton, consistent with the idea that singleton detection mode is an inefficient search strategy with respect to performance. Participants were more prone to stimulus-driven attentional capture on singleton detection trials and were generally slower to report the target even when the distractor was absent. A similar pattern of performance was evident in accuracy.

Contrary to the idea that participants either search on the basis of stimulus salience (Bacon & Egeth, 1994; Leber & Egeth, 2006a, 2006b) or with a broad attentional window (Belopolsky & Theeuwes, 2010; Belopolsky et al., 2007; Theeuwes, 2004) because it is easier to do so effort-wise, we find evidence that participants actually found feature search trials, in which the target was presented among heterogeneous shapes, to be less effortful. Participants exerted more physical effort to reduce the number of trials when the upcoming task was singleton detection, being more motivated to avoid the need to perform such trials. This finding also runs counter to the axiom that more heterogeneous nontargets produce more "difficult" visual search (Anderson & Lee, 2023; Duncan & Humphreys, 1989). It is, however, consistent with the idea that the perceived difficulty of search is related to the efficiency of measured performance (Anderson & Lee, 2023).

It is worth noting that the singleton cost on feature search trials was numerically larger than what is typically observed when only feature search trials are performed, which is minimal to no cost (Bacon & Egeth, 1994; Leber & Egeth, 2006b). Apparently, the rapid switching between mini-blocks impaired participants' ability to restrict attention to circle stimuli. This may have stemmed from switch costs affecting the precision of goal-directed attentional control, or possibly some residual tendency to process the circle target on the basis of its feature contrast, as it was the only stimulus with rounded contours in the display. In any event, distractor costs were clearly reduced on feature search trials and search performance was overall more efficient, consistent with a more selective mode of attentional control, which participants found to be less mentally effortful.

Participants were overall highly motivated to reduce the number of trials across mini-blocks, with mean effort exerted approaching 90% of the calibrated maximal effort at the longer mini-blocks. This was likely influenced by the fact that participants were not informed that the experiment would continue until a set amount of time had passed, with participants assuming (incorrectly) that their effort would result in faster completion of the experiment. Although they were more willing to exert physical effort in advance of singleton detection trials, consistent with a comparatively stronger motivation to avoid such trials, the overall high motivation to reduce the number of trials in general may have understated the disparity in motivation between search types by way of a ceiling effect, a possibility explored more directly in Experiment 2.

Experiment 2

In Experiment 1, we found evidence that, contrary to widely held assumptions, participants were more motivated to avoid performing singleton detection trials, exerting more physical energy in exchange for the ability to reduce the frequency with which they engaged in singleton search. This suggests that participants actually found singleton detection more mentally effortful than feature search. Given the surprising nature of this result, we sought to replicate this preference using a more direct and potentially more sensitive test.

In Experiment 2, participants again alternated between completing mini-blocks of feature search and singleton detection trials, but now, instead of reducing the number of trials they needed to complete, they had the option of switching which type of search they needed to perform. By exerting their maximal effort on the hand dynamometer, participants could opt out of performing one type of search and instead perform the other. This manipulation directly pitted singleton detection against feature search, in a situation in which there was some cost in physical effort to switch tasks. Experiment 2 therefore probes for more than a mere preference between the two tasks, but rather a preference that is strong enough that participants would be willing to work physically to exercise that preference. If singleton detection mode is indeed more mentally effortful than feature search, participants should exert more physical effort in advance of singleton detection mini-blocks, especially as the length of the mini-block increases.

Method

Participants

Thirty-nine new participants were recruited from the Texas A&M University community using the same compensation and inclusion criteria (24 female, 15 male; $M_{\text{age}} = 18.5$ years [$SD = 0.7$ 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.

Apparatus and Stimuli

Identical to Experiment 1 with the exception of the display preceding each mini-block. The force meter no longer had increments with numbers indicated, and when completely filled was replaced with the word "Switch!," which appeared with the task name simultaneously changing from "CIRCLE" to "DIFFERENT SHAPE" or vice versa.

Design and Procedure

Identical to Experiment 1 with the following exceptions. The number of trials in each mini-block did not change with force applied to the hand dynamometer. Once participants had pressed the space bar, triggered a switch of task by filling the force meter, or after 10 s had elapsed, the force meter disappeared while the reference to the upcoming task remained for 2,000 ms; if the participant exerted enough force on the hand dynamometer to trigger a switch of task, the word "Switch!" appeared in place of the force meter and the upcoming search task referenced in the text on the screen changed.

Analytic Approach

Identical to Experiment 1, with the additional measure that participants who did not complete any trials using a particular search mode (since it was possible to always avoid one of the two search tasks with the exertion of physical effort) were not included in the analysis of search performance.

Results

Search Performance

Four participants always opted to switch away from singleton search trials and two participants always opted to switch away from feature search trials and therefore did not provide any valid observations for such trials. RT and accuracy were compared across conditions for the remaining participants. An ANOVA on RT revealed a main effect of distractor presence, $F(1, 32) = 33.77$, $p < .001$, $\eta_p^2 = .513$ (Figure 3A), reflecting attentional capture by the salient distractor. There was also a main effect of search mode in which RT was overall slower on singleton detection trials, $F(1, 32) = 329.65$, $p < .001$, $\eta_p^2 = .911$. This slowing was evident even when restricting analyses to distractor-absent trials, $t(32) = 13.59$, $p < .001$, $d_z = 2.37$, consistent with the idea that searching for a salient singleton is generally inefficient. The interaction between distractor presence and search mode was not significant, $F(1, 32) = 1.97$, $p = .171$, although the magnitude of attentional capture was numerically larger on singleton detection trials. The distractor presence cost was individually significant on both singleton detection, $t(32) = 3.82$, $p < .001$, $d_z = 0.67$, and feature search trials, $t(32) = 8.66$, $p < .001$, $d_z = 1.51$. An ANOVA on accuracy mirrored this pattern, in this case producing a significant interaction in which the magnitude of attentional capture was elevated on singleton detection trials, in addition to the two main effects, Fs > 11.81, ps $< .003$ (Figure 3B).

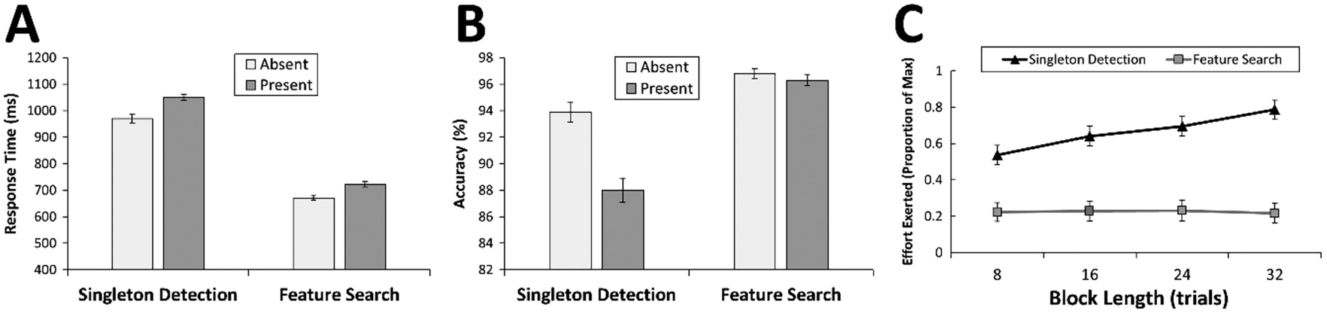
Physical Effort Exertion

The main effect of the search mode was robustly significant, $F(1, 38) = 34.23$, $p < .001$, $\eta_p^2 = .474$ (Figure 3C), with participants exerting more physical effort to switch away from performing singleton detection trials. There was also a significant main effect of block length, $F(3, 114) = 10.41$, $p < .001$, $\eta_p^2 = .215$, and a significant interaction, $F(3, 114) = 12.09$, $p < .001$, $\eta_p^2 = .241$, owing to the fact that the amount of physical effort exerted tended to increase with block length for singleton detection trials while remaining largely unaffected by block length for feature search trials. The observed physical effort exertion resulted in an average of 456.2 ($SD = 474.9$) more feature search than singleton detection trials being completed by participants.

Discussion

Experiment 2 robustly replicates the key finding from Experiment 1 in that participants were more motivated to avoid singleton detection trials, in this case exerting more physical effort to switch which type of search they needed to perform. When given the choice, participants preferred to complete mini-blocks requiring a feature search for a circle among heterogeneously shaped nontargets and were willing to exert physical effort to exercise that preference. The difference in trials completed between the two search conditions was substantially larger than in Experiment 1, likely owing to the fact that participants could switch which task they completed in Experiment 2 rather than reduce the number of trials in a given block, which participants were in general highly motivated to do across search conditions in Experiment 1. We again see evidence that participants find singleton detection to be the more effortful mode of searching.

Figure 3
Results for Experiment 2



Note. (A) Mean RT, (B) mean accuracy, and (C) mean physical effort exertion. Error bars in all panels reflect ±1 within-subjects standard error (Cousineau, 2005; Morey, 2008). RT = response time; ms = milliseconds; max = maximum.

Although singleton detection mode again resulted in robustly slower responses, consistent with less efficient search, elevated distractor costs were only observed with respect to accuracy, in contrast to Experiment 1. This inconsistency was likely influenced by the fact that some participants contributed very few trials to some cells in the analysis of search performance, resulting in more variable estimates of performance.[1] Indeed, several participants only ever opted to complete one type of search, contributing zero observations for the type of search they avoided, although other participants exhibited a similarly strong preference that resulted in mean RTs derived from only a handful of mini-blocks. In any event, participants clearly displayed less efficient performance on singleton detection trials, and a more complete replication of the full pattern of RT results is provided in Experiments 3 and 4.

It is also worth noting, as indicated by the fact that two participants did not complete any feature search trials, that a preference for feature search mode was not universal. Although there was a significant preference for feature search at the group level, with participants generally exerting effort to avoid singleton detection, a small number of participants exhibited a clear preference for singleton detection, exerting effort to avoid feature search. It is interesting to speculate on why this might be, which Experiment 3 will further speak to, and this reflects an issue we will return to in the General Discussion. As will be further demonstrated in Experiments 3–5, however, participants on the whole find feature search to be less mentally demanding than singleton detection, inconsistent with the idea that searching for a salient target in a homogeneous display is less effortful than searching for a feature-defined target in a heterogeneous display.

Experiment 3

In Experiment 3, we sought to extend the findings of Experiment 2 to a situation in which singleton search was not strictly mandatory. To this end, Experiment 3 replicated Experiment 2 with the exception that on singleton detection trials, the target was only ever a diamond. The target was still described as the "unique shape" in task instruction, but it was not necessary to search for the target on the basis of its uniqueness. As a result of this design change, the target was also primed on singleton detection trials with the same frequency as it was on feature search trials, repeating in identity on every trial, such that any positive effect of priming on task difficulty would be equated across search types. Indeed, intertrial priming of target shape has been shown to reduce attentional capture by salient singletons, which could potentially contribute to the reduced distractor costs observed on feature search trials (Pinto et al., 2005; but see Lamy et al., 2006). With targeted training, participants can learn to search for singleton targets of a fixed shape using feature search mode, although without training, stimulus-driven attentional capture consistent with singleton detection mode is typically observed (Cosman & Vecera, 2013; Leber & Egeth, 2006a, 2006b; Leber et al., 2009). Experiment 3 therefore provides a strong test of whether participants tend to search for a singleton in a manner that is more mentally effortful than an alternative mode of searching that is available to them given the constraints of the task.

Method

Participants

Forty-eight new participants were recruited from the Texas A&M University community using the same compensation and inclusion criteria (26 female, 21 male [one no response]; $M_{\text{age}} = 19.1$ years [$SD = 2$ 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.

Apparatus, Stimuli, Design, and Procedure

Identical to Experiment 2 with the exception that the target was only ever a diamond in singleton detection mini-blocks.

Analytic Approach

Identical to Experiment 2. Additionally, RT and physical effort exertion were compared between Experiments 2 and 3.

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[1] The magnitude of attentional capture on singleton detection trials was an extreme outlier for one participant (>4 *SD* below the mean), who completed only one miniblock of eight singleton detection trials. With the RT data for this participant removed, the interaction is significant, $F(1, 31) = 8.45$, $p = .007$, $\eta_p^2 = .214$.

Results

Search Performance

Two participants always opted to switch away from feature search trials and therefore did not provide any valid observations for such trials. RT and accuracy were compared across conditions for the remaining participants. An ANOVA on RT revealed a main effect of distractor presence, $F(1, 45) = 60.04$, $p < .001$, $\eta_p^2 = .572$ (Figure 4A), reflecting attentional capture by the salient distractor. There was also a main effect of search mode in which RT was overall slower on singleton detection trials, $F(1, 45) = 86.70$, $p < .001$, $\eta_p^2 = .658$. This slowing was evident even when restricting analyses to distractor-absent trials, $t(45) = 5.56$, $p < .001$, $d_z = 0.82$, consistent with the idea that searching for a salient singleton is generally inefficient. The interaction between distractor presence and search mode was also significant, $F(1, 45) = 14.09$, $p < .001$, $\eta_p^2 = .239$, with the magnitude of attentional capture being elevated on singleton detection trials. The distractor presence cost was individually significant in both singleton detection, $t(45) = 8.34$, $p < .001$, $d_z = 1.23$, and feature search trials, $t(45) = 6.64$, $p < .001$, $d_z = 0.98$. An ANOVA on accuracy revealed only a significant main effect of distractor presence, $F(1, 45) = 6.74$, $p = .013$, $\eta_p^2 = .130$; the main effect of search mode was marginally significant, $F(1, 45) = 3.45$, $p = .070$, $\eta_p^2 = .071$, and the interaction was far from significant, $F(1, 45) = 0.55$, $p = .461$, although in both cases the pattern of results was in the same direction as RT, inconsistent with a speed-accuracy tradeoff (Figure 4B).

Physical Effort Exertion

The main effect of the search mode was significant, $F(1, 47) = 5.18$, $p = .027$, $\eta_p^2 = .099$ (Figure 4C), with participants exerting more physical effort to switch away from performing singleton detection trials. There was also a significant main effect of block length, $F(3, 141) = 7.01$, $p < .001$, $\eta_p^2 = .130$, and a significant interaction, $F(3, 141) = 4.04$, $p = .009$, $\eta_p^2 = .079$, owing to the fact that the amount of physical effort exerted tended to increase more strongly with block length for singleton detection trials compared to feature search trials. The observed physical effort exertion resulted in an average of 158.3 ($SD = 465.4$) more feature search than singleton detection trials being completed by participants. Consistent with the idea that individuals differed in the extent to which they engaged in singleton detection mode and that this level of engagement had consequences for the motivation to avoid such trials, the cost in RT associated with singleton detection versus feature search trials was robustly correlated with the overall mean difference in effort exerted between the two types of searches, $r = .547$, $p < .001$ (Figure 4D).

Comparison of Experiments 2 and 3

Consistent with the benefit of intertrial priming, mean RT was significantly faster on singleton detection trials in Experiment 3 compared to Experiment 2, $t(77) = 7.65$, $p < .001$, $d = 1.77$. Mean RT did not differ significantly for feature search trials across experiments, $t(77) = -0.32$, $p = .751$, which is expected given that these trials were identical across experiments. The magnitude of attentional capture did not significantly differ for singleton detection, $t(77) = 0.39$, $p = .697$,[2] or feature search trials across experiments, $t(77) = 1.32$, $p = .190$. Participants exerted significantly more effort on singleton detection mini-blocks in Experiment 2 compared to Experiment 3, $t(85) = 3.06$, $p = .003$, $d = 0.66$, while the difference in effort exertion on feature search mini-blocks did not significantly differ across experiments, $t(85) = -0.89$, $p = .374$.

Discussion

Experiment 3 replicates the key findings of Experiment 2, in this case in a situation in which it was possible to search for the shape singleton target on the basis of its shape identity rather than on the basis of its feature contrast. It was also the case that the target was primed equally often (repeated every trial), such that any beneficial effects of target repetition on the perceived mental effort of searching were equated across tasks. Performance was again less efficient on singleton detection trials, and participants again found such trials to be more mentally effortful, being more strongly motivated to avoid the need to perform singleton search.

The difference in effort exerted on singleton detection trials was substantially reduced in Experiment 3 compared to Experiment 2, which corresponded to a less robust performance decrement in RT associated with singleton detection trials in Experiment 3. In fact, the larger the performance decrement associated with singleton detection versus feature search trials for participants in Experiment 3, the larger the disparity in physical effort exerted between the two search modes. Collectively, these relationships provide strong evidence supporting the idea that search efficiency and perceived mental effort are tightly linked. For the participants who did not incur as strong of a performance decrement on singleton detection trials, either because they engaged in feature search for a diamond or were otherwise able to exploit the consistency of the target on singleton detection trials, search for a singleton target was comparatively less demanding.

Experiment 4

Across three experiments, we see evidence that people are more willing to exert physical effort to minimize the need to search for a shape singleton target relative to a feature-defined target in a heterogeneous display, suggesting that singleton detection, and the corresponding propensity toward distraction, is more effortful than feature search. In Experiment 4, we asked how such findings square up against subjective reports of effort. Participants again completed mini-blocks of singleton detection and feature search, but now they could not influence the task they needed to perform or the block length. The grip component was simply removed from the experiment. At the end of the experiment, we asked participants to rate the subjective difficulty of each of the two search tasks, along with how efficiently they felt they performed each task and how enjoyable they found each task to be.

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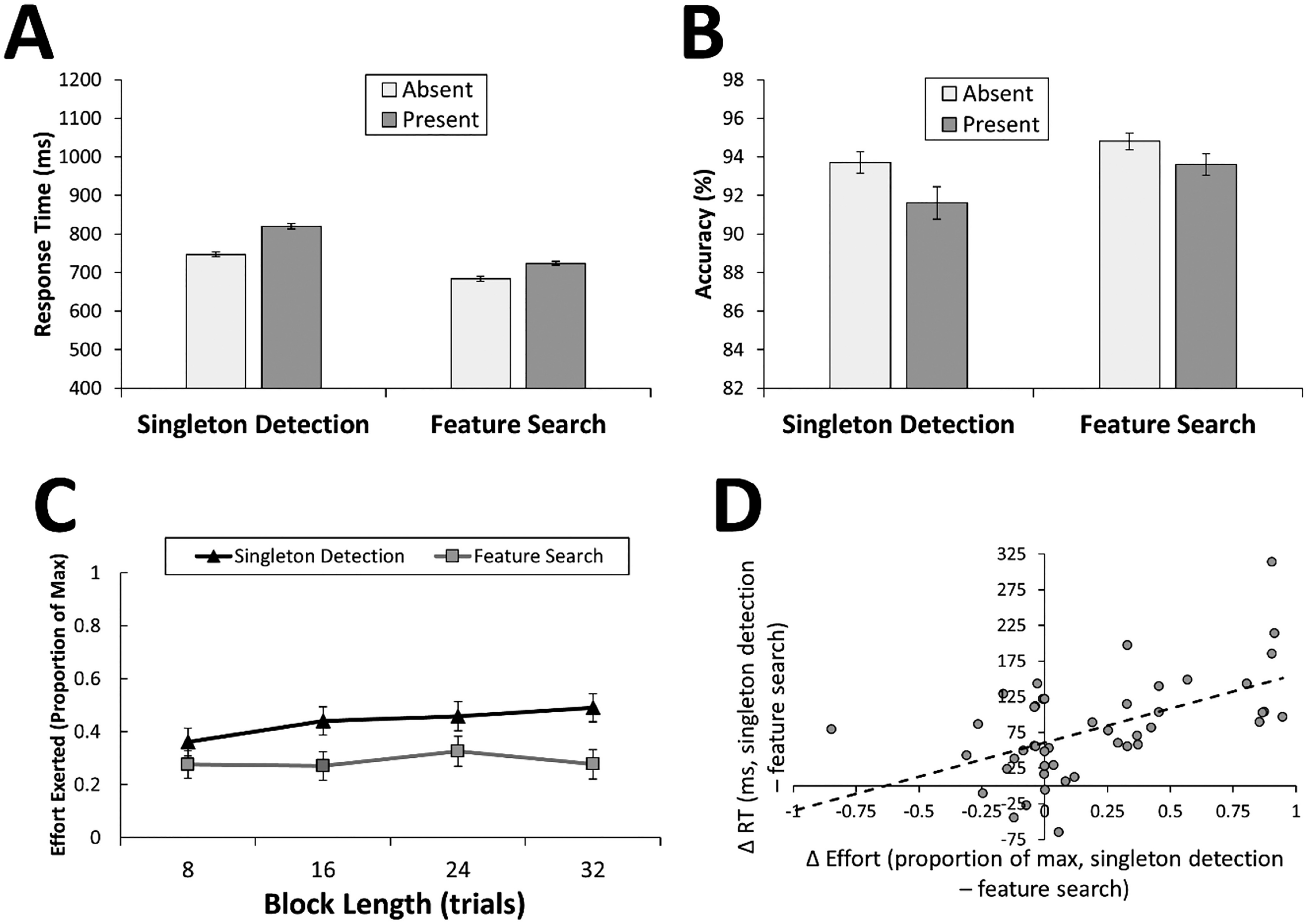
[2] The magnitude of attentional capture on singleton detection trials was an extreme outlier for one participant in Experiment 2 (>4 *SD* below the mean), who completed only one miniblock of eight singleton detection trials, but even with the capture score for this participant removed, the difference in capture between experiments was still not significant, $t(76) = 1.51$, $p = .136$.

Figure 4
Results for Experiment 3



Note. (A) Mean RT, (B) mean accuracy, (C) mean physical effort exertion, and (D) the relationship between RT costs and physical effort exertion. The dashed line represents the least squares regression equation for this relationship. Error bars in all panels reflect ±1 within-subjects standard error (Cousineau, 2005; Morey, 2008). RT = response time; ms = milliseconds; max = maximum.

Method

Participants

Forty-four new participants were recruited from the Texas A&M University community using the same compensation and inclusion criteria (31 female, 12 male [one no response]; $M_{\text{age}} = 18.6$ years [$SD = 0.9$ 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.

Apparatus, Stimuli, Design, and Procedure

Identical to Experiment 2, with the exception that the force meter was removed from the preview display for each mini-block (participants were simply informed of the parameters of the upcoming mini-block for up to 6,000 ms or until they pressed the space bar), the hand dynamometer was not used in the experiment, five sets of six mini-blocks with 32 trials per mini-block were completed, and participants completed a brief questionnaire after they completed the main task. Practice was also shorter, concluding with four mini-blocks of 16 trials each following the untimed practice. In the questionnaire, participants viewed two search displays (one from a singleton detection trial and one from a feature search trial) and rated how difficult they found each task (1 = *not at all difficult*, 10 = *very difficult*), how enjoyable they found each task (1 = *not at all enjoyable*, 10 = *very enjoyable*), how fast they thought they were at each task (1 = *not at all fast*, 10 = *very fast*), and how proficient they thought they were at each task (1 = *not at all proficient*, 10 = *very proficient*) using a 10-point Likert scale.

Analytic Approach

Search performance was analyzed in the same manner as Experiments 1–3. To probe participants' subjective reports of effort, we analyzed each subjective report measure using paired samples *t*-tests comparing ratings for the two search tasks. To further probe the relationship between participants' subjective reports of effort and their performance in the two search tasks, we also correlated the costs in accuracy and RT associated with singleton detection versus feature search trials with the mean difference in ratings for the two search tasks.

Results

Search Performance

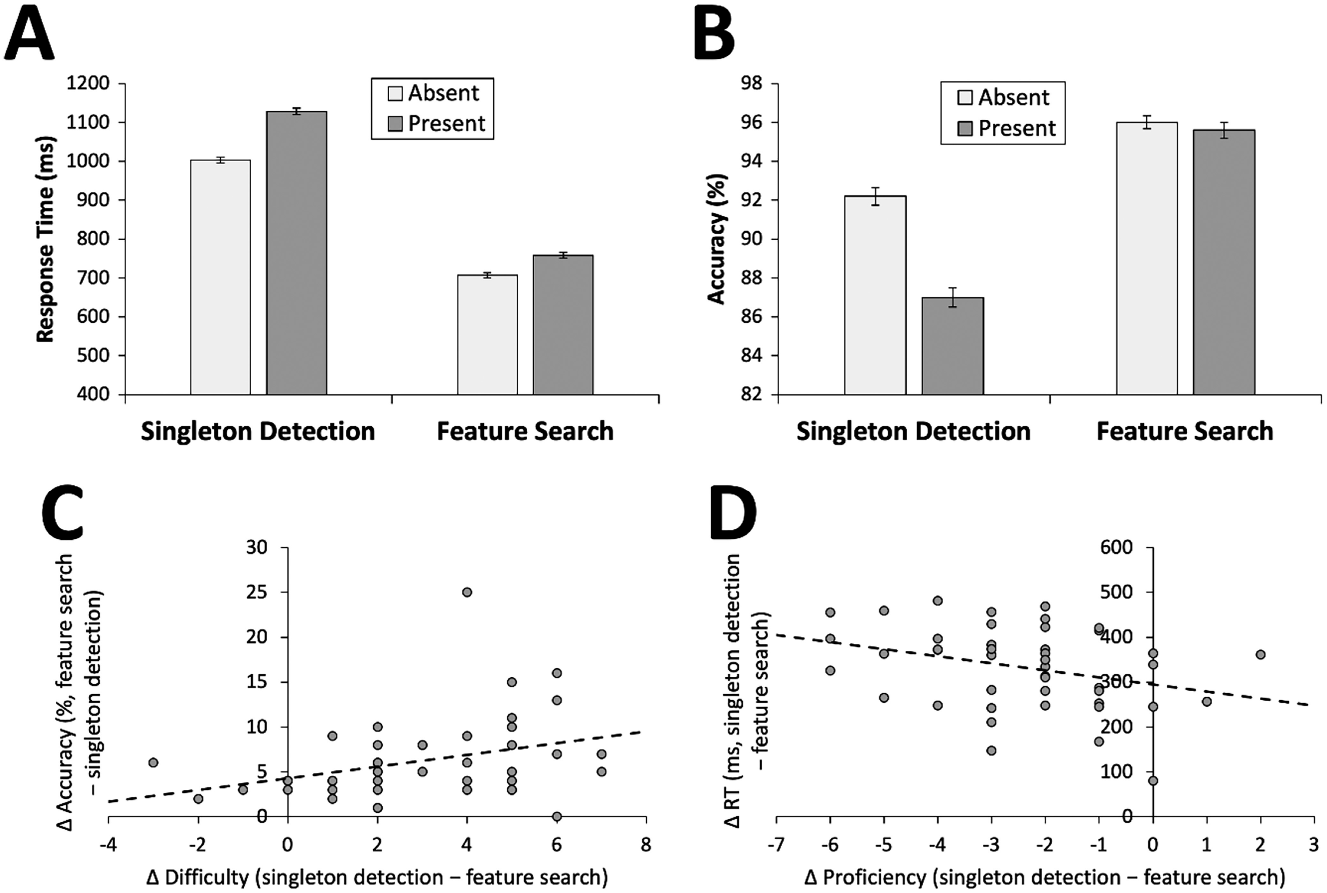
An ANOVA on RT revealed a main effect of distractor presence, $F(1, 43) = 407.74$, $p < .001$, $\eta_p^2 = .905$ (Figure 5A), reflecting attentional capture by the salient distractor. There was also a main effect of search mode in which RT was overall slower on singleton detection trials, $F(1, 43) = 584.81$, $p < .001$, $\eta_p^2 = .932$. This slowing was evident even when restricting analyses to distractor-absent trials, $t(43) = 21.41$, $p < .001$, $d_z = 3.23$, consistent with the idea that searching for a salient singleton is generally inefficient. There was also a significant interaction between distractor presence and search mode, $F(1, 43) = 91.39$, $p < .001$, $\eta_p^2 = .680$, reflecting greater vulnerability to attentional capture on singleton detection trials. The distractor presence cost was individually significant on both singleton detection, $t(43) = 16.94$, $p < .001$, $d_z = 2.55$, and feature search trials, $t(43) = 14.12$, $p < .001$, $d_z = 2.13$. An ANOVA on accuracy mirrored this pattern, with the same main effects and interaction, $F\text{s} > 47.85$, $p\text{s} < .001$ (Figure 5B).

Subjective Report

Paired samples t-tests revealed significant effects for all subjective report measures (see Table 1). Participants reported that singleton detection was more difficult than feature search, $t(43) = 8.25$, $p < .001$, $d_z = 1.24$, consistent with the idea that searching for a salient singleton is more mentally effortful than searching for a specific feature. Participants also reported that singleton detection was less enjoyable than feature search, $t(43) = -6.31$, $p < .001$, $d_z = 0.95$, suggesting that participants also found searching for a salient singleton less enjoyable than searching for a specific feature. Lastly, participants reported that they were slower, $t(43) = -7.70$, $p < .001$, $d_z = 1.16$, and less proficient at singleton detection compared to feature search, $t(43) = -8.71$, $p < .001$, $d_z = 1.31$. Thus, participants appeared to be generally aware of their performance in the two search tasks. The cost in accuracy associated with

Figure 5

Results for Experiment 4



Note. (A) Mean RT, (B) mean accuracy, (C) the relationship between accuracy costs and difficulty ratings, and (D) the relationship between RT costs and proficiency ratings. The dashed lines represent least squares regression equations for these relationships. Error bars in all panels reflect ±1 within-subjects standard error (Cousineau, 2005; Morey, 2008). RT = response time; ms = milliseconds.

Table 1

Mean Ratings for Each Subjective Report Measure in Experiment 4

Measure	Singleton detection	Feature search
Difficulty	5.45 (2.13)	2.52 (1.64)
Enjoyment	3.23 (1.75)	5.86 (2.86)
Speed	5.43 (1.74)	7.75 (1.69)
Proficiency	5.18 (1.72)	7.59 (1.47)

Note. Standard deviations are presented in parentheses.

singleton detection versus feature search trials was correlated with the difference in difficulty ratings for the two search tasks, $r = .335$, $p = .026$ (Figure 5C), revealing that individual differences in participants' search performance predicted their subjective reports of effort. The cost in RT associated with singleton detection versus feature search trials was also correlated with the difference in proficiency ratings for the two search tasks, $r = -.315$, $p = .037$ (Figure 5D), providing converging evidence that participants were generally aware of their own search performance. No other correlations between search performance and subjective report measures were significant, $ps > .218$.

Discussion

In Experiment 4, we replicate the performance decrement associated with singleton detection trials and further show that participants perceive such trials as more effortful as revealed via self-report. This suggests that the representation of mental effort that influences participants' decisions concerning physical effort exertion in Experiments 1–3 is something that they have at least some measure of conscious access to. We also found that participants perceive singleton detection trials as less enjoyable, and report that their performance on these trials is less efficient than on feature search trials. Thus, participants not only appeared to be aware of the difference in effort between the two search tasks, but were also generally aware of their performance on these tasks. Individual differences in participants' search performance also predicted their subjective reports of both effort and performance, providing further support for the idea that mental effort and search efficiency are tightly linked. Together, these findings provide converging evidence that participants perceive singleton detection as more mentally effortful than feature search, and suggest that participants' willingness to avoid singleton detection trials in Experiments 1–3 may be at least partially driven by conscious awareness of differential task demand.

Experiment 5

In Experiment 4, we found that participants perceive singleton detection trials to be more difficult than feature search trials, supporting our prediction that the avoidance of singleton detection trials was driven by the avoidance of effort. However, in all of our experiments, participants displayed greater distractor costs on singleton detection trials. Recent evidence suggests that observers are to some degree aware of when their attention has been captured (Adams & Gaspelin, 2020, 2021), and it is likely that participants in Experiments 1–4 were aware that their attention was captured more often on singleton detection trials. Indeed, participants in Experiment 4 appeared to be aware of their performance on the two search tasks, and individual differences in participants' search performance predicted their subjective reports of both effort and performance. Thus, it is possible that participants did not avoid singleton detection trials because searching for a shape singleton target is itself more effortful, but instead simply avoided these trials because they are more likely to result in distraction. In Experiment 5, we attempted to identify whether this was the case by simply removing distractor-present trials. If the avoidance of singleton detection per se was driven by the avoidance of effort, participants should show a significant preference for feature search trials even when distractor-present trials are removed.

Method

Participants

Twenty-eight new participants were recruited from the Texas A&M University community using the same compensation and inclusion criteria (16 female, 10 male [three no response]; $M_{\text{age}} =$ 19.1 years [$SD = 1.4$ 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 $(1 - \beta) >$ 0.95 with $\alpha = .05$ to detect a main effect of search mode on physical effort exertion of half the size of that observed in Experiment 2 (computed using G*Power 3.1; Faul et al., 2007).

Apparatus, Stimuli, Design, and Procedure

Identical to Experiment 2 with the exception that distractor-present trials were removed and replaced with distractor-absent trials.

Analytic Approach

Identical to Experiment 2 with the exception that mean RT and accuracy were each subjected to a paired samples *t* test.

Results

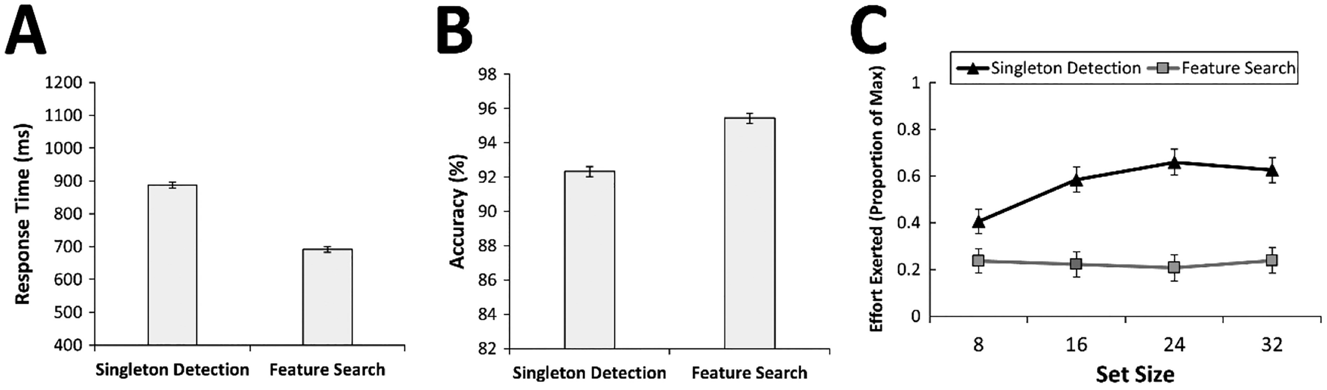
Search Performance

Two participants always opted to switch away from singleton search trials and therefore did not provide any valid observations for such trials. RT and accuracy were compared across conditions for the remaining participants. Participants were significantly slower, $t(25) = 11.52$, $p < .001$, $d_z = 2.26$ (Figure 6A), and less accurate, $t(25) = 5.25$, $p < .001$, $d_z = 1.03$ (Figure 6B), on singleton detection compared to feature search trials.

Physical Effort Exertion

The main effect of search mode was robustly significant, $F(1, 27) = 32.37$, $p < .001$, $\eta_p^2 = .545$ (Figure 6C), with participants exerting more physical effort to switch away from performing singleton detection trials. There was also a significant main effect of block length, $F(3, 81) = 9.27$, $p < .001$, $\eta_p^2 = .256$, and a significant interaction, $F(3, 72) = 10.09$, $p < .001$, $\eta_p^2 = .272$, owing to the fact that the amount of physical effort exerted tended to increase with block length for singleton detection trials while remaining largely

Figure 6
Results for Experiment 5



Note. (A) Mean RT, (B) mean accuracy, and (C) mean physical effort exertion. Error bars in all panels reflect ±1 within-subjects standard error (Cousineau, 2005; Morey, 2008). RT = response time; ms = milliseconds; max = maximum.

unaffected by block length for feature search trials. The observed physical effort exertion resulted in an average of 361.1 (*SD* = 331.7) more feature search than singleton detection trials being completed by participants.

Discussion

With no distractor-present trials and thus no influence of attentional capture, the results of Experiment 5 fully replicate the pattern of results from Experiment 2 in both search performance and physical effort exertion. Participants were again slower and less accurate on singleton detection trials, indicating that singleton detection is less efficient than feature search, even without any residual distractor costs or potential effects of distractor monitoring. That is, the manner of search itself appeared to be less efficient on singleton detection trials. Consistent with this difference in search performance, the same main effects and interaction were evident in physical effort exertion in Experiment 5, with participants again exerting more physical effort to reduce the need to perform singleton detection trials. Our findings provide clear evidence that, above-and-beyond any influence of elevated distraction on singleton detection trials, participants simply find the demands of searching for a shape singleton greater than the demands of searching for a specific shape in a heterogeneous display. Although Experiment 5 rules out distractor costs as an explanation for the motivation to avoid singleton detection, it would be interesting to see whether participants would still be so motivated if there were no salient distractors and the target shape was always held constant as in Experiment 3, which future studies might consider testing.

General Discussion

Across five experiments, we tested the assumption that singleton detection is less mentally effortful than feature search. Consistent with previous evidence, we observed inefficient search performance on singleton detection trials compared to feature search trials, with participants being generally slower and also more prone to stimulus-driven attentional capture (Bacon & Egeth, 1994; Lamy & Egeth, 2003, 2006a, 2006b; Leber et al., 2009). However, when participants were given the option to exert physical effort to reduce the number of trials within a block or switch the type of search for the upcoming block, participants showed a clear preference for performing feature search over singleton detection. This preference persisted even when we manipulated the task so that singleton detection mode was not strictly mandatory (Experiment 3). Moreover, participants reported that singleton detection was subjectively more difficult than feature search (Experiment 4), suggesting that the avoidance of singleton detection trials was at least partially driven by conscious awareness of differential task demand. Lastly, this preference persisted even when distractor-present trials were removed, suggesting that this preference was not simply driven by the avoidance of distraction (Experiment 5). Thus, in contrast to widely held assumptions, singleton detection mode is in fact the more effortful mode of searching, and it does not seem to be the case that this mode of searching can be explained as a means of minimizing the effort required to identify the search target.

Overall, the present findings challenge long-standing assumptions about why observers search on the basis of stimulus salience and/or with a broad attentional window. Bacon and Egeth (1994) originally proposed that observers prioritize salient stimuli when the target is itself salient because it is easier to search in this way, choosing to minimize effort at the expense of efficient search performance. Other researchers have largely adopted this assumption, suggesting that observers search on the basis of stimulus salience (Leber & Egeth, 2006a, 2006b; Leber et al., 2009) or with a broad attentional window (Belopolsky & Theeuwes, 2010; Belopolsky et al., 2007; Theeuwes, 2004) because it is less mentally effortful than searching for a specific feature or with a more restricted attentional window. In contrast to this assumption, we found that participants perceive singleton detection as more mentally effortful than feature search, and are willing to exert physical effort to avoid performing singleton detection trials. The influence of search efficiency on mental effort apparently overshadows any reduction in mental effort conferred by searching on the basis of salience and/or searching with a broad attentional window. Thus, when given the option, participants showed a clear preference for a search mode that was both less mentally effortful and more efficient.

If singleton detection mode is in fact the more effortful mode of searching, this leaves us with a conundrum: Why do observers search on the basis of stimulus salience when this search mode is more mentally effortful and less efficient than searching for a specific feature? As many researchers have suggested, it is likely that singleton detection mode is simply the default mode of searching in many situations. Notably, the target in many additional singleton studies is also a shape singleton; in such cases, observers may default to singleton detection mode, either because task demands encourage them to do so or because they have learned to use this search mode in similar situations. However, when task demands encourage the use of feature search mode (Bacon & Egeth, 1994; Lamy & Egeth, 2003) or when observers learn to use this search mode in a particular context (Cosman & Vecera, 2013; Leber & Egeth, 2006a, 2006b; Leber et al., 2009), they no longer appear to default to singleton detection mode. One interpretation of the results of the present study is that, as a general rule, observers do not engage attentional processes aimed at selectively processing particular stimuli or features unless the demands or the task and/or instruction require it. From prior research, it seems clear that most observers do not seek to maximize performance in attention tasks (e.g., Irons & Leber, 2016, 2018), and Anderson (2021) hypothesized that observers generally default to more automatic modes of information processing. In the present study, we observed inefficient search performance on singleton detection trials, even when singleton detection mode was not strictly mandatory (Experiment 3). Thus, consistent with previous evidence, participants appeared to default to singleton detection mode on these trials. However, when given the option of which task to perform, participants showed a clear preference for trials that encouraged the use of feature search mode.

Interestingly, while most participants avoided singleton detection trials, a small number of participants in Experiments 2 and 3 actually showed a strong preference for these trials. What can account for these individual differences in participants' search behavior? Notably, the cost in performance associated with singleton detection trials was correlated with the amount of effort exerted between the two search tasks, as well as subjective reports of effort for the two search tasks. Thus, as participants displayed worse performance on singleton detection trials, they perceived these trials as more effortful and showed a greater willingness to avoid these trials. Critically, these findings can potentially explain the small number of participants who showed a strong preference for singleton detection trials. Specifically, these participants may have searched on singleton detection trials more selectively, either effectively restricting attention to uniquely shaped stimuli (Experiment 2) or diamond-shaped stimuli (Experiment 3), leading them to perceive these trials as less effortful and show a stronger preference for these trials. In this regard, the observed correlation in Experiment 3 provides converging evidence for the idea that mental effort varies as a function of how an individual searches.

Differences in search strategy are not the only reason why some individuals may be less susceptible to attentional capture on distractor-present trials. Another possibility is that participants differed in their attentional control abilities. Individual differences in intelligence and working memory capacity have been shown to predict many attentional control abilities, including the ability to override attentional capture by salient (Fukuda & Vogel, 2009, 2011; Gaspar et al., 2016) or reward-related stimuli (Anderson et al., 2011; Anderson & Yantis, 2012). Thus, it is possible that some participants had greater attentional control abilities than others, leading them to display better performance on singleton detection trials, which in turn reduced the effort required to find the target on such trials. Yet another possibility is that these participants may have differed in their experience with a particular search mode. Previous evidence suggests that observers' search strategies can be shaped by prior experience, leading them to search more efficiently (Kim et al., 2022) and override attentional capture by salient stimuli (Cosman & Vecera, 2013; Leber & Egeth, 2006a, 2006b; Leber et al., 2009). Thus, it is possible that some participants had greater experience with a particular search mode, leading them to display better performance on singleton detection trials. It is also possible that these factors may interact with each other. For example, individual differences in working memory capacity have been shown to predict whether observers persist in using a more efficient search strategy (Robison & Unsworth, 2017). Future research should attempt to clarify the role of all of these factors in determining how effortful an observer finds a given visual search task.

In all of our experiments, we observed significant attentional capture on feature search trials. This differs from many previous studies, in which attentional capture is overridden (Bacon & Egeth, 1994; Leber & Egeth, 2006b) or even suppressed or "reversed" (producing a distractor presence benefit) on these trials (Gaspelin & Luck, 2018a; Gaspelin et al., 2015, 2017). Critically, we think this discrepancy is likely due to the frequent switching between search modes in our study. Most studies that have observed no attentional capture on feature search trials have had participants consistently use a single search mode (Bacon & Egeth, 1994; Leber & Egeth, 2006b). However, in our study, participants frequently switched between the two search modes. It is possible that this made it difficult to fully override attentional capture on feature search trials, as participants may need consistent experience with a particular search mode to override attentional capture. It is also worth noting that the studies that observed distractor suppression used the same target and distractor colors throughout the study. However, in our study, the colors of the target and distractors frequently switched. As multiple studies have shown, distractor suppression is not observed in this case (Gaspelin & Luck, 2018a), and only emerges as participants gain experience with a particular distractor color (Gaspelin & Luck, 2018a; Vatterott & Vecera, 2012; Vatterott et al., 2018). This likely explains why we observed significant attentional capture on feature search trials.

While we assume that the avoidance of singleton detection trials was largely driven by the avoidance of effort, it is likely that the present findings were at least partially driven by attempts to minimize errors or time on task. Previous evidence suggests that observers often avoid performing cognitively demanding tasks, even when controlling for differences in task performance (Dunn et al., 2016; Kool et al., 2010; Westbrook et al., 2013). However, recent evidence suggests that subjective reports of effort are correlated with the perceived error likelihood and time demands of a task (Dunn et al., 2019). In the present study, participants not only perceived singleton detection trials to be more effortful than feature search trials, but were slower and less accurate on these trials. Moreover, individual differences in participants' search performance predicted both their avoidance of singleton detection trials and their subjective reports of effort. Thus, it is likely that the avoidance of singleton detection trials was at least partially driven by attempts to minimize errors or time on task. With that said, there is ample evidence that observers often choose not to search in a manner that would have maximized performance (e.g., Anderson, 2021; Anderson & Lee, 2023; Irons & Leber, 2016, 2018; Lee et al., 2022; Nowakowska et al., 2017), and the time needed to complete the grip requirement in the present study (especially in Experiments 2 and 3 in which 100% of calibrated maximal effort would trigger a task switch) would have worked against millisecond-level time-savings on individual trials. The results of Experiment 4 clearly contradict the idea that singleton detection was in fact subjectively easier. Furthermore, when ITIs are adjusted such that exerting more physical effort cannot result in faster task completion and participants are explicitly informed of this, they still exert just as much physical effort to reduce the set size of heterogeneous displays compared to when ITIs are not adjusted in this way (Anderson & Lee, 2023); it is worth noting that these findings from Anderson and Lee (2023) were in a context in which the time savings associated with physical effort exertion would be more substantial than in the present study, making it unlikely that a drive to minimize time on task would have had a comparatively stronger effect in the present study. It, therefore, seems unlikely that the relative speed of performance between singleton detection and feature search trials can provide a complete account of why participants exerted physical effort in the manner in which they did, nor a drive toward performance maximization more broadly. Nonetheless, future research should attempt to disentangle the roles of effort minimization and performance maximization in observers' preference for search conditions.

While we largely explain our findings in terms of effort, it is also possible that our findings could be explained in terms of how difficult or (un)pleasant participants found the two search tasks. Other researchers have often used such terms interchangeably, alternately referring to singleton detection as "easier" or less "effort-intensive" and feature search as more "effortful" or "cognitively demanding" (Bacon & Egeth, 1994; Leber & Egeth, 2006a, 2006b). Indeed, in the context of visual search, effort and difficulty are intricately linked (Anderson & Lee, 2023), and it is also the case that more difficult and effortful tasks are generally perceived as less pleasant. Regardless of whether the present findings are explained in terms of effort or difficulty, these findings are inconsistent with any account in which singleton detection reflects a more advantageous or otherwise desirable manner in which to search, in contrast to widely held assumptions. With that said, we think it is unlikely that our findings can be purely explained in terms of how pleasant participants found the two search tasks. Indeed, while participants in Experiment 4 rated singleton detection trials as both more difficult and less enjoyable than feature search trials, only the difficulty ratings correlated with individual differences in participants' search performance. Thus, while we think our findings could be equally well explained in terms of effort or difficulty, they cannot be purely explained in terms of pleasantness.

The present study further develops methods introduced by Anderson and Lee (2023) using physical effort exertion as a window into mental effort. In Anderson and Lee (2023), the manipulation of physical effort was tied directly to the composition of visual search arrays, while in the present study, it was tied to the number of trials in a block or which of two tasks would be performed. The methods employed in the present study are thus more flexible and could be applied to essentially any pair of cognitive tasks to determine which of the two is more mentally effortful. This general approach offers a distinct advantage over methods in which participants simply choose which of two tasks to perform. While such an approach has been successfully used to assess attentional capture (Belopolsky et al., 2010), switch costs (Ort et al., 2017, 2018), and optimal strategy use in visual search (Irons & Leber, 2016, 2018), the approach used in the present study allows us to directly link participants' preferences for a particular search task to the effort costs associated with that task. Future research could leverage this general approach in a variety of different ways to provide unique insights into the nature of mental effort more broadly.

Lastly, the findings of our study provide an important caveat to the idea that the choice of how to cognitively process information is driven by the principle of effort minimization, at least with much of any situational flexibility (e.g., Kool et al., 2010; Vogel et al., 2020; Westbrook et al., 2013). Our findings are consistent with the idea that individuals employ default modes of information processing and tend to stick with a given mode even when it is situationally suboptimal with respect to effort demands and/or the optimality of task performance. These default modes of information processing may be rooted in effort minimization and/or performance maximization broadly construed (see, e.g., Anderson, 2021), but at least in the context of visual search, it does not appear that observers make online adjustments to the manner in which they process information to fine-tune performance. Rather than change how they process singleton detection displays, especially in Experiment 3 in which it was possible to use the same search strategy employed on feature search trials, participants would sooner exert physical effort to avoid singleton detection trials altogether.

In summary, in contrast to widely held assumptions in the field, we found that singleton detection mode is in fact the more mentally effortful mode of searching. Our findings are inconsistent with the idea that observers choose to engage in less efficient modes of searching specifically to minimize the effort required to complete the search, and in fact readily engage in a default mode of searching even when it is both less efficient and more mentally effortful. When given the option, participants prefer to engage in feature search and are even willing to exert physical effort to shift the balance of search demands toward feature search and away from singleton detection. This preference persisted even when singleton detection was not strictly mandatory, and appeared to be partially driven by conscious awareness of task difficulty. Moreover, this preference did not appear to be driven by the avoidance of distraction. Together, these findings challenge long-standing assumptions about why observers search the way that they do.

Constraints on Generality

The present study examined attentional processes in a sample predominantly comprising undergraduate students enrolled in a psychology course at Texas A&M University. Visual search abilities have been shown to vary across the lifespan (e.g., Hommel et al., 2004), and it is possible that developmental processes may differentially impact either feature search or singleton detection. Cultural differences in local versus global visual information processing have been identified, with individuals from East Asian cultures exhibiting a more pronounced global bias than individuals from Western cultures (e.g., McKone et al., 2010), which could have implications for proficiency with singleton detection versus feature search. Future research should examine whether similar findings to those reported in the present study are observed across the lifespan and extend to participants from a variety of cultures (Masuda, 2017), including East Asian cultures.

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