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TUTORIAL REVIEW

Getting a grip on visual search: Relating effort exertion to the control of attention

Brian A. Anderson[1] · David S. Lee[1] · Molly R. McKinney[1] · Andrew Clement[2]

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Abstract
Humans are generally biased to conserve energy, limiting the exertion of physical and mental effort. The need for attention to selectively process perceptual information is a ubiquitous part of mental life, but how mentally effortful is the process of finding the target of a visual search, and how much mental effort is required to focus attention in the face of potentially distracting stimuli? Does learning from demands on physical effort shape the control of attention, much like rewards and punishments? In this tutorial review, we provide an overview of a novel approach to probing the mental effort involved in visual search and the control of attention more generally. Situations are created in which exerting physical effort, via a hand dynamometer, can modify the demands of a visual search task. More specifically, participants can exert physical effort to reduce the putative mental effort required to find a target. When comparing across search conditions, this approach can reveal the conditions that participants are willing to physically work to achieve, with implications for the mental effort associated with these conditions. We also introduce a reciprocal approach in which demands on physical effort, and their association with the visual search task, are manipulated, providing an opportunity to examine how the control of attention is shaped by these effort demands. Some practical considerations for the implementation of these novel approaches are discussed, as are potential new research directions for which these approaches are well suited.

Keywords Visual search · Attentional control · Mental effort · Cognitive demand · Energy

The principle of effort minimization in cognition

Anyone who has witnessed someone aggressively jockey for a parking space near the gym instead of accepting one of the many open spaces on the other side of the lot has an intuition for the fact that people have a natural tendency to minimize effort exertion. Even when the intent of the trip is to exercise, the prospect of walking across a parking lot remains aversive. Although certainly not without exception (Clay et al., 2022; Pellegrini et al., 2007; Rosenbaum et al., 2014; Wasserman & Brzykcy, 2015), humans and other animals exhibit a bias to conserve energy as a limited resource.

✉ Brian A. Anderson
brian.anderson@tamu.edu

[1] Department of Psychological and Brain Sciences, Texas A&M University, College Station, TX 4235 TAMU77843-4235, USA

[2] Department of Psychology and Neuroscience, Millsaps College, Jackson, MS, USA

The principle of effort minimization has been extensively investigated in the context of physical exertion. It is well established that, when given the option, people generally prefer tasks that minimize physical effort (e.g., Klein-Flügge et al., 2016; Kurniawan et al., 2010; Prévost et al., 2010), a preference that is thought to reflect an adaptive tendency to conserve energy resources for potential use in the future (Cheval & Boisgontier, 2021; Lieberman, 2015). More recently, this same principle of effort minimization has been extended to the domain of human cognition. When individuals choose which of two cognitive tasks to perform, they show a preference for the less effortful task, which can be operationalized with respect to working memory demand, the frequency with which switches in task rules occur, or whether an additional cognitive operation needs to be performed over stimuli (e.g., Kool et al., 2010; Shenhav et al., 2017; Zhang & Leber, 2024). Mental effort can be viewed within the framework of economics, with an intrinsic cost to exerting effort that must be weighed against any benefits that the investment of effort might bring (Kool & Botvinick, 2018). The "cost" or aversiveness of mental effort is clearly illustrated by the fact that participants are willing to accept aversive thermal stimulation 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; see also Anderson, 2024b). Rewards are also devalued as a function of the cognitive effort required to obtain them, consistent with the idea that mental effort is perceived as costly (Apps et al., 2015; Westbrook et al., 2013, 2020).

Visual search constitutes a cognitive task that likely involves some degree of mental effort. Selective attention is required to prioritize task-relevant information and filter out or ignore task-irrelevant information (Egeth & Yantis, 1997; Wolfe, 2020, 2021), with computations performed over priority maps in the brain (Anderson, 2019; Bisley & Mirpour, 2019; Sprague & Serences, 2013; Wolfe, 2021). In dense displays with heterogeneous stimuli, multiple shifts of attention are often required before the target of search is identified (Wolfe, 2021), and task-irrelevant stimuli can vary in their propensity to cause distraction that must be overcome (Duncan & Humphreys, 1989; Luck et al., 2021; Theeuwes, 2010). Once a stimulus is selected, visual input must be compared against a representation of a searched-for stimulus in activated memory (Reinhart & Woodman, 2015; Woodman & Arita, 2011; Woodman et al., 2013) in order to arrive at a decision concerning how to act and whether to continue searching (Wolfe, 2021). Although the component processes and computations involved in visual search have received considerable research focus, we know little about the relationship between visual search and mental effort.

The concept of mental effort is well represented in both historical and contemporary thinking concerning the control of attention. Human observers have been noted to adopt visual search strategies that are inefficient with respect to performance, which has been hypothesized to reflect a drive toward effort minimization (Irons & Leber, 2016, 2018; Zhang & Leber, 2024; see also Clarke et al., 2024; Nowakowska et al., 2017), and subjective reports of the effort associated with adopting more optimal search strategies are negatively associated with the use of these strategies (Irons & Leber, 2018). The theory that observers sometimes intentionally search for physically salient stimuli rather than try to restrict their attention to stimuli that possess a particular task-relevant feature, even when doing so renders them more vulnerable to distraction by physically salient non-targets (i.e., singleton detection mode), is predicated on the idea that searching for salient stimuli is minimally effortful (Bacon & Egeth, 1994). A recent theoretical account of involuntary mechanisms of attentional control emphasizes that these mechanisms often serve to minimize the need for controlled and effortful information processing (Anderson, 2021). However, direct measurement of mental effort in the study of visual search is lacking, and treatment of the concept of mental effort in the literature on visual search remains largely theoretical.

Willingness to exert physical effort as a window into mental effort

Quantifying mental effort in the study of visual search is not without challenges. One could simply ask people how effortful they perceive different search tasks to be, but such a question has a transparent demand characteristic, and answers may be biased by assumptions about what seems like it *should* be effortful on the surface (see Firestone & Scholl, 2016). It is also unclear how much conscious access people have to the mental effort required of different visual search tasks, especially given that people have limited conscious access to the manner in which they direct their attention (Adams & Gaspelin, 2020, 2021; Anderson & Mrkonja, 2021, 2022; Horowitz & Wolfe, 1998; Theeuwes et al., 1998; Võ et al., 2016).

Another approach would be to require that people choose between the performance of two different visual search tasks, under the assumption that they would prefer the easier task. This approach has proven fruitful in research on cognitive effort more broadly (e.g., Kool et al., 2010). This approach, however, only indirectly indexes perceived effort, resting on the assumption that no additional factors unrelated to effort would significantly contribute to task preference. Task preference is also likely to be a somewhat noisy measure, being influenced by a drive toward exploration (e.g., Gottlieb et al., 2013) and a need to learn about task difficulty by making choices and experiencing the consequences. Without strong a priori assumptions concerning what factors would make a task more effortful, choice data are difficult to interpret in the context of perceived effort. Finally, this approach forces an arbitrary distinction between tasks that participants might not otherwise be inclined to make (they are required to select one of the two tasks), potentially overstating the degree to which the magnitude of choice preference maps onto the magnitude of difference in perceived effort.

We have developed an alternative and more direct approach to quantifying the extent to which a visual search task is perceived as effortful that involves relating physical effort to mental effort. The researcher can create situations in which exerting physical effort reduces the putative mental effort of a visual search task, for example by reducing the number of items that need to be searched through, and the point of interest becomes how much physical effort participants are willing to exert across different visual search conditions. This approach rests on the assumption that, if one visual search task is more mentally effortful than another, participants will be motivated to exert more physical effort to offset some of the mental effort. The approach does not require any direct equivalence between units of physical and mental effort, as it relies on relative comparisons of physical effort expenditure across search conditions. Our approach bears some resemblance to other approaches to relating physical effort to mental effort (e.g., Feghhi & Rosenbaum, 2019; Feghhi et al., 2021; Potts et al., 2018), but rather than choose between a physical and a cognitive task, participants can exert physical effort to modify the nature of a visual search task.

Some advantages of this approach include the fact that the primary dependent measure, physical effort exerted, offers a metric that is itself intrinsically effort-related. It avoids a transparent demand characteristic; although participants may perceive a general expectation that they should exert some physical effort in the task, they are not provided with any basis upon which to differentially allocate that effort across task conditions. In fact, they might perceive the experiment as a general test of how motivated they are to exert physical effort, rather than how differentially motivated they are to exert physical effort as a function of factors of the task that they might not otherwise consider. They could choose to exert no physical effort at all, which is always an option available to them, such that the experiment does not force participants to draw a distinction between task conditions that they might not otherwise be inclined to distinguish. That is, participants must be sufficiently motivated such that they believe that the exertion of any physical effort will be worth the cost in mental effort reduction, explicitly engaging in the kind of economic considerations described by Kool and Botvinick (2018). In addition, physical effort exerted provides a continuous measure, in contrast to a binary choice of task on each trial.

Willingness to endure other undesirable situations or expend other resources can be considered in the context of tradeoffs with mental effort. The core logic of the approach we are suggesting assumes that physical energy is a limited resource and that the exertion of physical effort is to some degree aversive or otherwise undesirable, and other manipulations that tap into these components of physical effort can be considered. For example, situations could be created in which participants begin the task with a fixed amount of money and can pay a small portion of that money to make a search task easier, similar to effort-discounting paradigms (e.g., Westbrook et al., 2013). Likewise, situations could be created in which participants can avoid more challenging task conditions if they accept an electric shock or another aversive outcome (e.g., Vogel et al., 2020). We prefer the manipulation of physical effort, as physical effort demands can be varied continuously and are more directly analogous to demands on mental effort. For example, physical energy, like mental energy, is a resource that recovers over time with rest, placing the two on a more similar playing field. This is not true of money, which participants may be more inclined to hold onto, either due to an attempt to maximize gains or minimize losses. Aversive outcomes, such as electric shock, are difficult to manipulate on a continuous level (outcomes that are no longer aversive or so aversive as to cause distress would need to be avoided) and may provide too strong a deterrent (see Anderson, 2024b). Nonetheless, while we find several advantages to pitting physical effort against putative mental effort, several benefits of our approach would extend to the manipulation of other properties that could trade off with putative mental effort.

The manipulation of physical effort in the study of visual search goes beyond questions of mental effort with respect to its potential scientific utility. For example, as will be further explored later in the text, one can examine how attentional biases are shaped by physical effort exertion, how arousal induced by the exertion of physical effort influences search, and how the anticipation of physical effort alters attentional priority. There are manifold potential ways in which the experimental manipulation and/or measurement of physical effort exertion can enrich our understanding of the function of attentional control and the mechanisms that underlie it.

Manipulating and measuring physical effort expenditure: Use of a hand dynamometer

Methodological considerations

When implementing measurements and manipulations of physical effort in the study of visual search, there are several issues that need to be taken into consideration. Most manipulations in a visual search task are instantiated at the level of a single trial, such as display set size or whether a salient distractor is present in the display. This provides the experimenter with considerable flexibility in how variables are manipulated and permits repeated observations within each experimental condition, which promotes measurement reliability (Rouder et al., 2023). It would therefore be preferable to use a measurement of physical effort exertion and a manipulation of physical effort demands that can similarly be implemented at the level of a single trial. In this context, a fast-twitch exercise such as a single lift of an object would be preferable to an epoch of time spent running on a treadmill or pedaling on a stationary bicycle, the latter of which might be better used for examining how exercise influences attention (e.g., Bullock & Giesbrecht, 2014; Palmer et al., 2013).

Given that visual search experiments are typically performed in front of a computer screen, there are also practical considerations surrounding the feasibility and efficiency of integrating the physical and mental task. Requiring an individual to repeatedly get up from their chair in front of the computer to perform even a brief physical exercise would be cumbersome; if the experiment were to involve eye tracking, it would likely be unfeasible. It would be ideal to use a means of manipulating and measuring physical effort that can be done while the body remains relatively stationary and in an upright sitting position, which eliminates a wide variety of physical exercises that we might consider. To fully integrate physical effort with the visual search task, it would also be necessary to use a physical task that can be performed without mechanically interfering with the ability to make manual responses.

Another important consideration is the ability to obtain a measure of physical effort exertion that can be (a) read out by a computer in near real-time and (b) immediately incorporated into the task experience such that what the participant sees adapts to their physical energy output. Under these circumstances, exerting physical effort can have an immediate impact on the putative mental effort required of the visual search task, and it is possible to provide participants with immediate feedback concerning their effort exertion if the goal is to use the degree of effort exertion as a manipulation. Finally, to facilitate comparisons between individuals in between-subjects designs or to preserve meaningful variability between individuals for individual differences analyses, and to avoid floor and ceiling effects for some participants in within-subjects designs, the physical effort expected of a participant should be calibrated to their unique physical abilities or strength. Requiring performance of a fixed physical task or act, such as lifting a dumbbell of a prespecified weight, might be trivial for some individuals and overbearing for others, regardless of how motivated they might be to perform the task.

Applying physical force to a hand dynamometer provides a means of measuring and manipulating physical effort exertion that addresses all of these issues (see Fig. 1). A hand dynamometer measures the amount of force applied by contracting the hand muscles. The dynamometer can be held in one hand while behavioral responses to the visual search display are made with the other. Squeezing the hand dynamometer requires minimal movement of the arm, such that it is possible to apply considerable force to the dynamometer while remaining quite still for eye tracking. The application of force to the hand dynamometer can be executed rapidly, allowing for trial-level manipulation and measurement of force output. The amount of force applied to the hand dynamometer provides a continuous measure of physical effort exertion, which can be digitized and rapidly read out by a computer, allowing for nearly seamless integration of force output with what the participant sees on the screen. Force output can be easily translated to a proportion of a calibrated threshold, such as a person's maximal sustained grip strength, allowing for a measure of effort exertion that accounts for individual differences in physical strength or ability.

Fig. 1 Hand dynamometer. Force is applied by contracting the hand muscles, analogous to squeezing a stress ball. The dynamometer shown in this image is a Vernier HD-BTA model used by the authors in the experiments described in this paper

Historical context

Hand dynamometers have been used across a variety of psychological science contexts for over 70 years. Leveraging the continuous nature of force output, studies have tasked participants with translating the strength of a perceived force to force applied to a hand dynamometer, using force output as a means of quantifying perception and charting psychophysical functions (Stevens & Mack, 1959). Measured grip strength has been used in neuropsychological evaluation, particularly when the lateralization of brain lesions is of interest (e.g., Dodrill, 1978). At more advanced ages, grip strength as measured using a hand dynamometer has been shown to be predictive of cognitive decline (e.g., Fritz et al., 2017; Taekema et al., 2010).

In the domain of cognition, rewards are devalued as a function of the physical effort demands – as manipulated via a hand dynamometer – required to obtain the rewards (Hartmann et al., 2013; Kurniawan et al., 2010; Rodman et al., 2021), similar to how cognitive demand can devalue rewards (e.g., Apps et al., 2015; Westbrook et al., 2013, 2020). The prospect of reward motivates more vigorous physical effort exertion on a hand dynamometer even when reward prospect is signaled subliminally (Pessiglione et al., 2007). Cognitive and physical effort, with physical effort manipulated via a hand dynamometer, have been shown to be sensitive to domain-general motivational signals in the brain (Schmidt et al., 2012). In these cases, there is an explicit tradeoff between physical effort and the value of an outcome at stake. The methods introduced in this tutorial review build on this design concept, pitting physical effort against the demands of an attention task and the potential value of making the task less cognitively demanding.

Device considerations

A wide range of hand dynamometers are available for purchase, including devices with both analog and digitized indicators of force output. For the purposes of integration with a visual task, however, it is necessary that the hand dynamometer to be used has a digitized output that can be integrated with computer software via a USB or other connection. Far fewer hand dynamometers that are available for purchase possess this functionality, as most are intended to serve as stand-alone devices to be used in a clinical or exercise/training setting. A market analysis of hand dynamometers suitable for the types of research described in the paper is beyond the scope of this tutorial review. However, for the experiments described here, a Vernier HD-BTA model hand dynamometer was used with a Vernier Go!Link adapter to provide USB interface. For context, as of the writing of this review, the combined list price of this dynamometer and adapter is US$199.

As a USB or other port-type device, a computer program that can both generate and display the experimental stimuli and read the device output for integration with stimulus generation is needed. We programmed our experiments in MATLAB using Psychophysics Toolbox functions (Brainard, 1997) and a plugin available on GitHub (https://github.com/lionel-rigoux/vernier-toolbox) for integrating the dynamometer with MATLAB. Under this setup, the hand dynamometer produces a MATLAB variable when queried, the value of which corresponds to the output of the dynamometer in Newtons. As long as the hand dynamometer can output signal through a computer port, any computer code capable of monitoring/querying that port and controlling the experiment display should suffice.

Implementation

Setup. We generally have participants hold the hand dynamometer and apply force with their left hand, while making behavioral responses using their right hand. It would certainly be feasible to have every participant hold the hand dynamometer in either their dominant or their non-dominant hand, although when force is interpreted in proportion to a calibrated threshold (see next section), the measurement will account for individual grip strength; in this way, the distinction between dominant and non-dominant hand simply becomes another factor contributing to individual differences in raw grip strength, which are effectively factored out by the calibration procedure. Maintaining consistency in which hand is used to hold the dynamometer simplifies the experimental setup by avoiding the need to move the computer running the experiment or the dynamometer and its connecting wire to the other side of the apparatus, which risks coming into contact with other pieces of equipment that make up the apparatus (e.g., an eye tracker). Especially when eye tracking, the hand dynamometer can be held with the arm resting on the table, such that only the hand and wrist substantively move when applying force.

Calibration. We calibrate individual grip strength as the median of non-zero values read out by the hand dynamometer over three epochs in which the participant squeezes the dynamometer as forcefully as they can (Anderson & Lee, 2023; Lee et al., 2024; see Park et al., 2021, for a similar procedure). The exclusion of zero values (and near-zero values consistent with the dynamometer resting in the hand) accounts for the response time between a message on the screen indicating that the participant should apply force and the actual application of force. The use of three epochs avoids overweighting a potential outlier application of force and accounts for a small amount of fatigue, as the epochs occur in close succession. In general, given the use of the median, but especially given that values are recorded during the "ramp up" of force while the hand muscles are contracting, the measure of calibrated grip strength obtained via this method will be below the force of a person's actual maximal voluntary contraction. However, this is of trivial consequence, as the calibrated threshold is computed in the same manner for each participant, thus achieving the goal of normalization to individual grip strength, and furthermore, the primary measure of interest involves a comparison of physical force applied between two or more conditions. As will be further contextualized below, the force thresholds used in the experiment can be any proportion of this calibrated grip strength, including more than 1.0 if desired (see, e.g., Chong et al., 2015). It is incumbent upon the experimenter to choose thresholds that require legitimate effort to meet without falling outside of the bounds of what a person could realistically meet with sufficient motivation throughout the course of the experiment.

Integration with the visual task. In most experimental situations, it is helpful to be able to provide participants with feedback concerning how much force they are applying to the hand dynamometer in near real-time. This allows them to know how they would need to adjust their physical effort to achieve whatever threshold of output would be necessary to accomplish a task-related goal. We accomplish this by means of a "force meter," which is a visual depiction of a bar that fills in proportion to the amount of force applied (see Fig. 2). In practice, this amounts to drawing an empty (outline) rectangle on the screen and another filled rectangle inside of it, which is anchored to the bottom of the empty rectangle and the height of which is scaled to the force readout by the hand dynamometer. The force on the hand dynamometer is computed as a proportion of the calibrated grip strength (see prior section), with 1.0 reflecting force that matches the calibrated grip strength. A value of 1.0 or higher will result in a filled rectangle that encompasses the entire extent of the empty rectangle (note that this threshold is to some degree arbitrary, and the force meter could be just as easily scaled to something greater or less than 1.0), and anything less will result in the empty rectangle being filled in direct proportion to the read-out force.

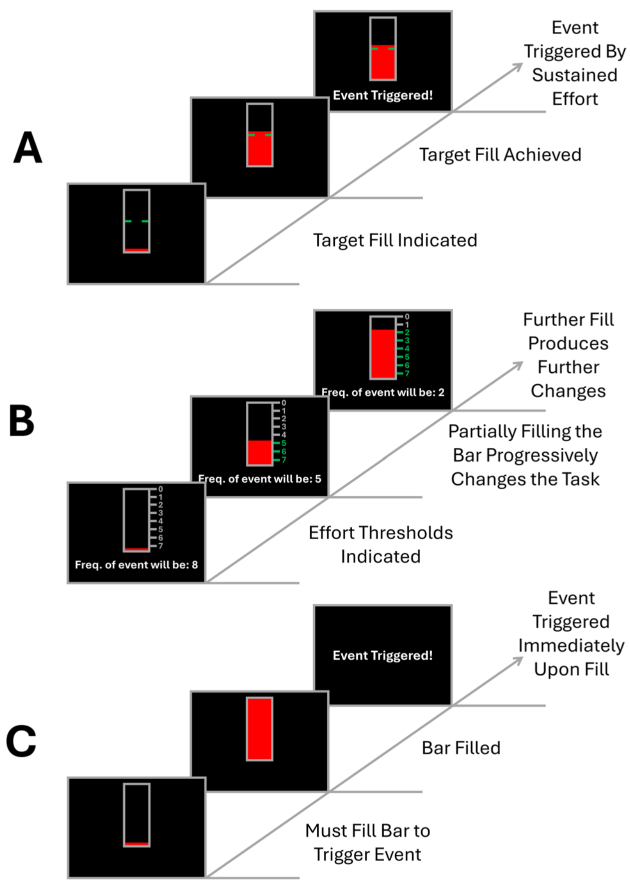

Fig. 2 Examples of how physical force, as illustrated using a force meter (i.e., the fill of the bar), can be related to a cognitive task. (**A**) Maintaining force above a set threshold for a set period of time triggers an event. In Anderson and Lee (2023), this event was the removal of an item from a search array. (**B**) The frequency of an event is changed in proportion to force applied. In Lee et al. (2024), this was the number of search trials that needed to be performed in the upcoming block of trials. (**C**) Entirely filling the force meter triggers an event. In different experiments in Lee et al. (2024), the triggered event was a changing of the search task that needed to be performed in the upcoming block of trials

Marker lines can be set on the force meter, either a single marker line to indicate a target force threshold (see Fig. 2A) or a series of marker lines similar to those on a thermometer (see Fig. 2B). A bar without marker lines can be used when complete fill of the force meter is required to trigger a particular outcome (Fig. 2C). The task can be set up such that filling the force meter beyond the single marker line for a set amount of time triggers an outcome (Fig. 2A), or that progressively filling the force meter beyond each of the individual marker lines triggers an outcome with each line surpassed (Fig. 2B). In the case of the latter, since the applied force can fluctuate and the fill of the force meter thus falls below a marker line that was previously surpassed, we programed the experiment such that the maximal fill achieved during the trial determines the outcome of effort exertion, which is indicated by marker lines immediately turning green when the fill surpasses them and remaining green even if the fill later falls below them (e.g., Lee et al., 2024, Experiment 1). Example studies throughout the remainder of the paper provide illustrations of how the visual search task can change as the force meter is filled.

Some additional recommendations for integrating a hand dynamometer with a visual search task, or really any cognitive task, include balancing the time between successive periods of the task in which grip force can be applied, the magnitude of the target force threshold required to trigger an outcome, and the amount of time required above threshold to achieve that outcome. An optimal balance here should result in neither participants becoming too fatigued to achieve an effect of applying force when motivated (e.g., pass the first marker line to effect some desired change in the search task) nor the task becoming too easy such that the maximal consequence of force can be consistently achieved with little motivation. We do not have a simple set of rules or a balancing equation to recommend here, only that care should be taken in piloting experiment designs. Another recommendation would be to allow sufficient time for participants to become familiarized with the visual search task before any grip manipulation is introduced. If participants are going to be deciding whether and how much physical effort to invest in light of how mentally effortful they perceive the visual search task to be, they should be making this decision with enough experience to have formed some intuition for what it is like to perform the task independent of any physical effort requirements. Finally, when introducing the grip component of the experiment, we recommend providing an example trial in which participants must use the hand dynamometer in order to observe how applying force impacts the task. As with the prior recommendation, this ensures that decisions concerning whether and when to invest physical effort are as informed as possible.

Proof of concept: Physical effort and canonical indicators of visual search "difficulty"

If the logic of the approach of creating tradeoffs between physical and mental effort advocated in the preceding text is defensible, we would expect participants to exert more physical effort when established theory would predict that the visual search task would be more effortful. A recent study by Anderson and Lee (2023) provides evidence in the affirmative. More specifically, in Experiments 1–3, we created a situation in which exerting physical effort could reduce the visual search set size. For every 50 ms that force greater than a specified threshold was applied to the hand dynamometer, one non-target item was removed from the search display. Each trial began with a 2-s period in which placeholder stimuli were presented, which were then replaced by search stimuli until the target was found; non-target items could be removed from the display by applying physical force during either epoch (with placeholders for non-targets being removable during the initial epoch). The placeholder display was included to allow for the removal of search items unconfounded by any dual-task interference caused by searching while interacting with the hand dynamometer. Of interest was how many items a participant would remove as a function of the putative difficulty of the search task and the physical demands of doing so (i.e., how much force was required to remove an item, which varied over trials). Figure 3A provides an example of what a trial in this design looked like.

Canonical indicators of search difficulty at the trial level include set size (larger set sizes are more difficult to search through when non-targets are heterogeneous) and non-target heterogeneity (more heterogeneous non-targets are more difficult to search through; Duncan & Humphreys, 1989; Huang & Pashler, 2005; Hulleman, 2010; Wolfe, 2000; Wolfe et al., 1989). More broadly, measured search slope (how long it takes to find the target as a function of the number of items in the display) provides an indicator of how difficult a visual search task is (Huang & Pashler, 2005; Hulleman, 2010; Wolfe, 1998, 2000). Visual search tasks that produce a relatively steep search slope have traditionally been characterized as "difficult" (e.g., Huang & Pashler, 2005; Hulleman, 2010), but the relationship between "difficulty" and perceived effort has remained elusive. Experiments 1–3 in Anderson and Lee (2023) leverage these canonical indicators of search difficulty to test whether they are related to the amount of

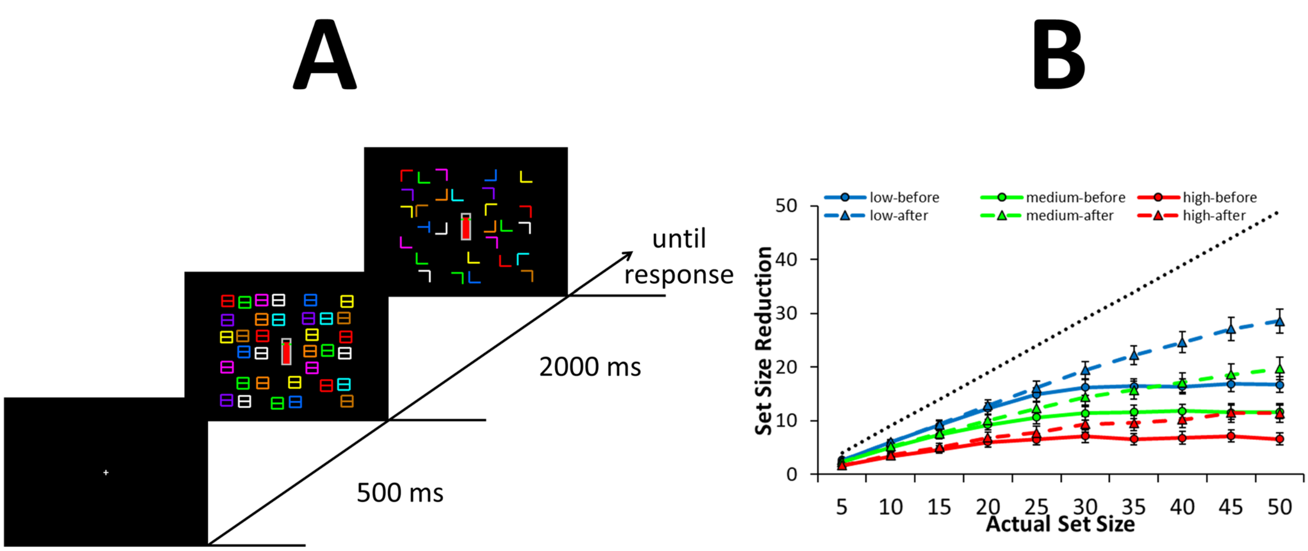

Fig. 3 (**A**) Example trial from Experiment 1 of Anderson and Lee (2023). Participants could remove items from the search array by applying physical force to the hand dynamometer, both before search commenced (during the placeholder display) and after (during the presentation of the search array). One item would be removed every 50 ms that the force meter was filled beyond a set threshold, which varied trial to trial (low, medium, high). (**B**) Behavioral data from Experiment 1 of Anderson and Lee (2023). The number of items removed with force, termed *set size reduction*, is indicated on the y-axis, and the actual starting set size is indicated on the x-axis. Set size reduction is shown both before search commenced (at the termination of the placeholder display) and after the trial had been completed by reporting the target, for three different levels of force required to remove items (low, medium, high). As is evident from the figure, there was a main effect of effort requirement, in which more items were removed when it was physically easier to do so, and a main effect of set size, with more items removed at larger set sizes. There was also an interaction by which sensitivity to larger set sizes was greater when the force required to remove items was lesser. All of this was true when set size reduction was measured both before and after search commenced

physical effort participants are willing to exert in order to reduce search set size.

In Experiment 1 of Anderson and Lee (2023), participants exerted increasing physical effort with increasing set size. Physical effort was expressed in terms of *set size reduction*, the number of items removed from the display using physical effort, which was measured separately at the termination of the placeholder display (or *before* search) and upon the conclusion of the trial (or *after* search). Participants were more willing to exert physical effort to reduce the set size as the set size increased, suggesting a relationship between set size and the perceived effort involved in finding the target (see Fig. 3B). That is, the more items participants needed to search through to find the target, the more items they were inclined to remove from the search task using physical effort. The number of items removed by exerting physical effort also scaled with the amount of physical effort required to remove an item from the display, with participants less inclined to exert physical effort when the burden of removing an item was higher, providing a manipulation check that the grip requirement was in fact effortful.

In Experiment 2, participants exerted more physical effort when non-targets were heterogeneous compared to homogeneous, with non-target heterogeneity mapping onto perceived mental effort as assumed in previous literature. Experiment 3 replicated Experiment 1 while controlling the time between trials, such that the removal of items from the display would not result in the experiment being completed any faster (a design feature that participants were explicitly informed of); in this case, the only benefit to the removal of non-targets from the display was the reduction in search effort required to find the target, yet participants robustly exerted physical effort in order to achieve this benefit. Across all three experiments, participants' measured search slope was predictive of the number of items they removed from the display before the search items were revealed from the placeholders (unconfounded by time spent searching, which would be expected to be longer for individuals with a steeper search slope), suggesting that individuals who found the search more difficult (as indexed by search slope) were the most motivated to exert physical effort in order to reduce search difficulty.

Experiments 4 and 5 of Anderson and Lee (2023) examined this relationship from the other direction, creating a situation in which participants could first choose how much cognitive effort to exert during visual search, with later implications for demands on physical effort. For the visual search task, participants were presented with arrays of red and blue stimuli in which one red and one blue target was present, adapting the *Adaptive Choice Visual Search (ACVS) task* pioneered by Irons and Leber (2016, 2018; see also Clement & Anderson, 2023; Hansen et al., 2019; Kim et al., 2021, 2024; Lee & Anderson, 2022; Lee et al., 2023). Only one of the two targets needed to be reported on each trial, allowing participants to decide whether to search among just the red or just the blue items. After each search trial, participants needed to apply physical effort to a hand dynamometer in order to progress to the next trial. Critically, one set of color stimuli was smaller than the other on each trial (making it easier to search through stimuli within that set to find a target), which varied unpredictably (i.e., sometimes there were fewer red and sometimes there were fewer blue items), while reporting a target of a particular color (e.g., red) was associated with a greater demand on physical effort. Of particular interest were trials in which demands on physical and mental effort conflicted: locating and reporting the easier-to-find target would trigger greater physical effort demands. On such trials, a joint influence of each demand on performance was evident, and most importantly, participants were increasingly willing to endure the more demanding physical effort requirement as search for the corresponding target became easier with an increasingly smaller set size.

The approach of Experiments 1–3 of Anderson and Lee (2023), adapting the putative demands of a visual search task as a function of physical effort exerted, could be applied in a wide variety of contexts as a window into what individuals find to be cognitively effortful. For example, the luminance or color contrast of a distractor could be adjusted with physical effort (perhaps for the upcoming block of trials), as could how far out in the periphery targets are presented when central fixation is enforced or how much crowding is present in the display. The approach of Experiments 4 and 5 of Anderson and Lee (2023) is more restricted to situations in which the same search task could be completed using at least two different strategies, although the spirit of the choice element of this approach is maintained in multiple of the other approaches described in the following section.

Case studies in the application of the method to broader scientific questions

The broader concept of using willingness to exert physical effort as a window into the perceived mental effort of visual tasks can be applied in a variety of ways to address a range of interesting and theoretically decisive questions. The following case studies highlight some of the ways in which this approach might be applied. These case studies are with respect to completed experiments (some already published and some yet to be published), while hypothetical cases that could be applied in future research are provided in the next section.

Comparison of mental effort across tasks

To answer the question of which of two tasks is the more mentally effortful one, we have used two related approaches, each of which involves the opportunity to exert physical effort in advance of a mini-block of trials (typically 8–32 trials). In one approach, participants have the option of exerting their maximal calibrated effort (which involves completely filling the force meter), which has the consequence of switching the task they will need to perform for that mini-block. This is not unlike asking participants which of two tasks they would prefer to perform (Kool et al., 2010), although it creates an intrinsic cost in effort to making the switch, requiring that any task preference participants might evidence be sufficient to motivate the expenditure of physical effort. Under these conditions, any task preference realized through physical effort expenditure suggests a preference that is at least to some degree effort motivated.

The second approach is to allow participants to reduce the number of trials in the upcoming mini-block by some number not to exceed the total number for the mini-block. In our prior work, we have used up to half the number of trials in the mini-block as the limit. Under these conditions, one might expect participants to be generally motivated to reduce the number of trials they need to complete, and thus the amount of mental effort they need to exert in general. However, if one task is more mentally effortful than the other, the motivation to exert physical effort to reduce the number of trials in a mini-block of that task might exceed that for the other task, resulting in an imbalance in effort exerted between mini-blocks of the two types of tasks.

We have used the two aforementioned approaches to provide evidence that feature search is preferred over singleton detection, suggesting that singleton detection may be perceived as more effortful than feature search (Lee et al., 2024). Furthermore, blocks in which distractors are presented infrequently are preferred over blocks in which distractors appear with high frequency, suggesting that resisting distraction is effortful (Anderson, 2024a). By varying the number of trials in a mini-block, the researcher can additionally probe for interactions between mini-block length and effort exerted; to the degree that the mental effort required of a task scales with the number of trials of that task that need to be completed, the difference in measured physical effort between the two types of tasks should scale with the number of trials in the upcoming mini-block. When implementing the approach in which participants can reduce the number of trials in the upcoming mini-block, we recommend programming the experiment such that it continues to generate new mini-blocks for a fixed duration of time, preventing substantially different overall experiment run times for participants who are and are not generally motivated to reduce the number of upcoming trials by exerting physical effort.

Stimulus frequency and mental effort

To answer the question of whether handling or otherwise processing a particular stimulus is mentally effortful, such as a task-irrelevant distractor and the corresponding need to resist distraction by the stimulus, an approach can be used in which the frequency of the stimulus can be modified by physical effort exertion. This is similar to the approach to modifying the number of trials in a mini-block described above, except that rather than the number of trials changing, the frequency with which a particular stimulus or type of stimulus is encountered in the upcoming mini-block changes. To provide a meaningful basis of comparison, participants should be given the option of either increasing or decreasing the frequency of the critical stimulus, in separate mini-blocks, to determine which direction of influence they prefer. Most compelling is to compare the difference in the amount of effort expended when decreasing versus increasing the frequency of the stimulus between two task conditions, one in which the stimulus is hypothesized to be more effortful to suppress (or otherwise process) than the other. We have used this approach to demonstrate that participants are motivated to exert physical effort to reduce the frequency of distractors, to a degree that is related to the magnitude of distractor costs, suggesting that resisting distraction is effortful (Anderson, 2024a).

Effort expenditure and attentional biases

Physical effort expenditure can be used as an unconditioned stimulus in an associative learning situation in order to study how effort expenditure shapes the allocation of attention. One approach would be to replace different levels of reward with different levels of required effort in the value-driven attentional capture design (Anderson et al., 2011; Anderson & Halpern, 2017; Kim & Anderson, 2019; see also, Kim & Anderson, 2021b). Different color-defined stimuli become associated with different levels of required physical effort exertion in an initial training phase, and then task-irrelevant stimuli can be rendered in these same colors in a subsequent test phase in which there are no more physical effort requirements and color is irrelevant to the task. One possibility is that attention would be biased by the color associated with the greatest effort requirement, with the effort association influencing attention in the context of aversive conditioning (e.g., Anderson & Britton, 2020; Kim & Anderson, 2021b; Schmidt et al., 2015). Another possibility is that attention would be biased by the color associated with the least amount of required effort, with the opportunity to progress without the need to exert physical effort serving as a reward (negative reinforcement). Recent evidence from our lab supports the former, with attention biased in favor of stimuli previously associated with high effort demand (McKinney et al., 2023).

Spatial attention has also been shown to be sensitive to reward learning and aversive conditioning (Anderson & Kim, 2018a, 2018b; Anderson et al., 2022; Chelazzi et al., 2014; Liao et al., 2023; Mine et al., 2021), and so one can ask similar questions with respect to the control of spatial attention. We conducted an experiment in which participants chose one of two stimuli to fixate on each trial, one presented to the left and the other to the right of initial gaze (conceptually similar to task choice in Kool et al., 2010). Following this directional eye movement, participants filled the force meter to a specified level using the hand dynamometer. One of the two directions of eye movement (counterbalanced across participants) was associated with a higher probability of comparatively high physical effort demand than the other. Participants generally learned to saccade in the direction associated with lesser physical effort demand, moving their eyes in a manner that minimized overall effort expenditure (Clement et al., 2022).

Potential future directions

The overarching approach of relating physical effort to the mental effort subsumed within visual search that we discuss in this paper could be purposed to address a wide variety of important questions. For example, numerous contributions of selection history to the control of attention have been identified, including contextual cueing, biases toward high-frequency target locations, and facilitated ignoring of high-probability distractors (for reviews see Anderson et al., 2021; Anderson, 2024c). Although such learning-dependent mechanisms of attentional control have been shown to facilitate search efficiency, they might also serve to reduce the mental effort required to find a target. To determine whether this is the case, the amount of physical effort exerted in order to reduce the mental effort of the search task (e.g., reduce search set size) could be measured with and without the benefit of selection history. That is, physical effort exertion could be compared between participants who are and are not exposed to statistical regularities in the search task that would be expected to facilitate search efficiency, with the prediction that the improved efficiency of search will reduce motivation to trade off mental effort with physical effort. Particularly compelling about this approach is the fact that participants are generally unaware of the contingencies that drive selection history-dependent effects (see Anderson et al., 2021; Grégoire & Anderson, 2019; Leganes-Fonteneau et al., 2018, 2019), such that conscious awareness of task contingencies and assumptions about how they might affect the difficulty of the task would not be responsible for driving physical effort exertion. In order to more effectively account for individual differences in willingness to exert physical effort, a baseline measurement of willingness to exert physical effort could be obtained for each participant and subsequent measurements compared against this baseline.

Another future direction could entail the assessment of domain-general mental fatigue. Does performing visual search make participants perceive the performance of subsequent cognitive tasks not requiring visual search to be more effortful than they otherwise would be, and vice versa, does performing non-search tasks render a subsequent visual search task more mentally effortful? Different non-search tasks could be used in this way to speak into which component processes putatively engaged by the non-search task are taxed by the performance of visual search.

Some other future directions include the use of effort exertion as a means of manipulating arousal, and how expectations of future effort exertion influence attentional control. In the case of manipulating arousal, participants could complete a visual search task with and without having recently exerted a high degree of physical effort on the hand dynamometer, which has been shown to transiently increase arousal (Nielsen & Mather, 2015). This could serve as a complement to research examining visual attention under threat-of-shock, but without the anxiety and strong negative valence associated with such manipulations of arousal (Kim & Anderson, 2020a, 2020b, 2021a; Kim et al., 2021). In the case of expectations concerning future effort, participants could complete a visual search task in a context that they do and do not associate with high upcoming physical effort demands. Perhaps the anticipation of physical effort demand results in reduced mental effort in visual search as a sort of compensatory mechanism of energy conservation, resulting in less efficient and/or more distraction-prone search, and perhaps attentional control is more broadly reduced in a high-effort context.

Limitations

As with any scientific methodology, the approaches for relating physical to mental effort discussed in this tutorial review are not without limitations. Willingness to exert physical effort to modify task conditions provides a window into the conditions that the participant prefers enough to physically work in order to achieve those conditions, but as with choice preferences (e.g., Kool et al., 2010), it is an assumption that putative mental effort is a key factor motivating this choice. Other factors related to mental effort, such as time on task, could influence motivation, and although we have taken efforts to equate time on task across conditions (e.g., Anderson & Lee, 2023), the subjective amount of time spent engaging in a mental operation could be perceived as aversive independently of the effort required to perform the task. This touches on a broader issue with respect to the difficulty of defining exactly what constitutes mental effort, as mental effort and the total amount of time spent engaging in a mental process are not independent.

Similarly, physical effort as measured via a hand dynamometer is the joint product of the magnitude of force exerted and the duration over which such force is sustained. Although demands on each can be independently manipulated, it is impossible to ever fully dissociate the two, as exerting effort necessarily involves the application of force over time. We prefer to vary the magnitude of force required rather than the duration over which a certain amount of force must be sustained in order to avoid manipulating the amount of time required to achieve a given force threshold. Indeed, this would confound the exertion of effort with the amount of time on task, which participants may be motivated to minimize. However, it is challenging to completely eliminate temporal variability between different effort thresholds, as a higher magnitude of force will necessarily take slightly longer to achieve given that muscle contraction itself unfolds over time.

The deterrent that the grip component of the task provides to the exercise of task preference is difficult to quantify, as participants may simultaneously feel some inclination to want to explore using the dynamometer in the context of the experiment and/or find the use of the dynamometer interesting, stimulating, or otherwise entertaining. Indeed, participants have been observed to occasionally self-administer an aversive electric shock when otherwise left to wait (Wilson et al., 2014), suggesting that boredom can motivate novelty seeking even when such stimulation is otherwise undesirable. It is also the case that there may be some degree of a demand characteristic motivating participants to apply force to the hand dynamometer at least some of the time. Such inclinations and curiosities would not be expected to confound any differences in effort exertion observed between task conditions, but they would to some degree minimize the benefits that the physical effort component has over mere choice of task as described when introducing the methodology. The use of a hand dynamometer to directly modify the conditions of a trial, as in Anderson and Lee (2023), most effectively circumvents some of the limitations surrounding the inference of effort from preference, but even this is not without assumptions concerning what exactly motivates a person to modify the task.

A unique advantage of using a hand dynamometer to measure physical force output is that it can provide a continuous measure of motivation to influence task conditions (e.g., Anderson & Lee, 2023). However, it is not the case that force output directly translates to perceived mental effort, for the kinds of reasons why participants might also be inclined to apply force to the hand dynamometer described in the preceding paragraphs. The methodologies described in this review are limited to relative comparisons between task conditions, and it is not the case that the amount of effort associated with a cognitive task per se can be directly quantified from force output, in the same manner that physical effort might be quantified with respect to a unit of force such as Newtons. While a hand dynamometer hypothetically provides the ability to obtain a continuous measure of perceived mental effort, this ability depends on the purity of reason why a participant might choose to apply force to it. As such, we recommend restricting data analysis to relative comparisons of effort expenditure across task conditions, which removes any general biases to want to interact with the hand dynamometer as a result of novelty seeking or a desire to explore.

Experiments utilizing physical effort as a manipulation, for example in the context of associative learning or arousal induction, are subject to related limitations concerning the purity of the manipulation. Effort demand, arousal, task difficulty, and perhaps the attentional demands of performing the task may be simultaneously impacted by the introduction of varying degrees of physical effort requirement. Even when the amount of time required to sustain force of multiple different thresholds is equated, more difficult effort demands come with a higher probability − however slight − that the participant will fail to meet the demand on first attempt, which could influence participants independently of the amount of effort they actually exert. These limitations are true of most any manner in which a researcher might manipulate physical effort demands, resulting in ambiguity that must either be acknowledged in the interpretation of findings or resolved through dedicated experimentation differently taxing the different ways in which a task of physical effort could affect a person.

Conclusions

Assumptions concerning the mental effort involved in visual search and the control of attention abound. Here, we reviewed an approach of relating physical to mental effort that can be flexibly applied to a range of theoretically motivated questions concerning the nature of mental effort. Several examples of the application of this approach were provided, some of which are consistent with long held theoretical assumptions about underlying mental effort (e.g., Anderson & Lee, 2023), one of which violates such assumptions (Lee et al., 2024), and some of which provide novel insights into less assumption-laden issues with respect to effort and attention (e.g., McKinney et al., 2023). Multiple novel applications of the proposed method were described, highlighting the broad flexibility of the approach. Indeed, the approach we reviewed here is by no means constrained to the domain of visual search and the control of attention, and could presumably be applied to the study of almost any mental task. For example, a similar approach was recently applied to the quantification of the mental effort involved in working memory maintenance (Xie & Zhang, 2023). Along with the applications reviewed here, such findings suggest that this approach provides a powerful tool to address a variety of questions regarding the nature of mental effort.

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